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SAND CONTROL IN HORIZONTAL WELLS IN HEAVY OIL RESERVOIRS

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EXECUTIVE SUMMARY

Horizontal wells are of great interest to most oil companies operating in heavy oil fields. Due to more extensive contact with the reservoir, horizontal wells allow fluid flow at lower *in situ* fluid velocities while providing total flows which are economic. While horizontal wells have the potential to make many more heavy oil reservoirs economic, one of the most pressing concerns has been proper well completion. Unfortunately, likely candidates for horizontal wells are mostly "quicksand" type formations and the critical velocities of sand in a wellbore are extremely low. Consequently, sand is very likely to enter the horizontal wellbore if no preventive measure is taken. Problems of sand production in a horizontal well are more complicated than in a vertical well due to the difficulty in cleaning sands from horizontal wellbores.

The present study discusses the problems of sand production in a horizontal well and offers recommendation for controlling them. Physical simulation of the top part of the horizontal well showed that both gravitational and inertial forces help minimize sand production. This will mean that increasing flow rates will decrease sand production from this section of the wellbore. Experimental evidence showed that selection of liner diameter and wire spacing are important parameters for wire wrapped screens in controlling sand production. Permeability damage due to particle mixing in the annulus between the liner and formation was quantified. It was shown that minimizing the annulus is of more importance in the case of smaller wire spacing, lower oil viscosity and thinner pay zone.

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Finally, a technique for cleaning horizontal wells was proposed. A slurry flow model was adopted in order to estimate the solid carrying capability of cleaning fluids.

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1.0 INTRODUCTION

Sand production is considered to be one of the major problems that have perplexed the petroleum industry. Every year the petroleum industry spends millions of dollars in sand cleaning, repair problems related to sand production and lost revenues due to restricted production rates.Consequently, sand control has been a research topic for over five decades. Uncontrolled sand production is very expensive due to additional operating expenses (such as pump change, well clean up, etc.), lost revenues, and creation of potentially hazardous situations. Some of the specific problems associated with sand production are:

- sand fill inside the hole
-casing or tubing which reduces or shuts off production
- sand accumulation in surface equipment
- erosion damage to down hole equipment
- creation of void spaces behind the casing leading to buckling
- problems of sand disposal
- major plugging problems in horizontal or slanted wells Additional expenses associated with sand production include clean out and disposal of sand and work over costs to return the well to production.

The lost revenue due to restricted or completely shut in production is often a hidden expense and not always considered in economic calculations. The production of sand in gas and oil wells is expensive and every effort should be made to control sand production.

A successful sand control scheme should involve:

- stopping sand movement and production of sand
- maintaining maximum well productivity

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- paying out treatment costs within a reasonable time.

As will be discussed later on, it is very difficult to optimize all the above criteria in a successful sand control scheme. Most of the early research work conducted by petroleum industry involved designing the largest practical sizes of gravels and liners with the notion that this will also lead to highest production rates. For many years, the philosophy of "if all sand production is stopped, the fluid production will be stopped" seemed to dominate the petroleum industry.Recent research efforts, however, have focused on complete sand control while maintaining highest well productivity.

1.1 Sand control Methods

Sand control methods may be classified as mechanical,chemical and mechanical/chemical. Mechanical methods of sand control prevent sand production by stopping the formation with liners, screens or gravel packs. Larger formation sand grains are stopped, and they in turn stop smaller formation sand grains. Chemical control methods involve injecting consolidating materials into the formation to cement the sand grains together preventing displacement. The most common chemical used is plastic. A liquid plastic is injected into a formation and over flushed with an inert fluid. The plastic hardens and binds the sand grains together into a rigid matrix. A combination of plastic consolidated gravel and screen maybe used to provide increased stability to the pack.

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1.2 Geological Considerations:

Sand production is known to be site specific. This is because depositional environments, physical and chemical characteristics of sand and clays, reservoir rock properties can all play an important role in determining the nature of sand movement. An understanding of how sands were originally deposited often provides some valuable insight into their properties and into determining an effective sand control technique.

The strengths of sandstones are developed by compaction, cementation by addition of minerals, and dissolution of sand grains at contact points. Cementation by minerals is the most important means of natural consolidation. The most common mineral cementing agents are quartz (SiO_2), calcite($CaCO_3$) and dolomite ($CaMgCO_3$). Some sandstone formations are trapped in environments with insufficient sources of cementing minerals or conditions that do not allow cementation. Consequently, the sand remains unconsolidated or weakly consolidated. This usually results in relatively high porosity and permeability formations. Almost all producing sandstone formations contain some clays and fines. Clays may be attached to sand grains, interbedded within the formation, or loosely arranged in the interstices and may have a major effect on formation permeability due to their fibrous shapes and large surface areas. Some sandstones are consolidated by clays acting as the cementing material. Such formations are very weak and subject to collapse when fluid flow begins.

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1.3 Reasons For Sand Production

Sand production occurs when the stress on the formation exceeds the strength of the formation. The formation strength is mainly derived from natural cementing material holding the sand grains together, but the sand grains are also held together by the cohesive forces due to immobile formation water. The stress on the formation sand grains is due to many factors, notably, tectonic actions, overburden pressures, pore pressures, stress changes from drilling and the drag forces on the producing fluids. Sand production is known to be sensitive to production rate. For semi-consolidated or unconsolidated sandstones, there is a rate below which sand may not be produced. However, for unconsolidated sands, the cementing agent is primarily detrital clay which provides little or no strength to withstand the formation stresses. Consequently, sand is produced at slightest movement of the reservoir fluid at the wellbore. For more competent sandstone formations, often no sand is produced at the initial stages of production.However, as the reservoir pressure declines, individual sand grains have to carry more overburden pressure, which increase the grain to grain stress in the formation and causes the cementing agent to fail. Consequently, sanding is often a problem at later stages of oil production from more competent reservoirs.

Sand production has often been related to water production. Some of the reasons for this are:

- increased total fluid production to maintain oil production rates increases the drag forces across the sand
- disturbance of the cohesive forces holding the sand grains together

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as the water phase becomes mobile.

- increased drag forces due to two-phase flow and mobility of the wetting phase
- dissolution or softening of the natural cementing materials.

"Quicksand" is a term often applied to completely unconsolidated sands. This type of sands has no effective cementing agent and is held together only by small cohesive forces and compac .on. Sand production for these reservoirs begins immediately with fluid production as sand flows readily with oil, water or gas.

1.4 Historical Review of Sand Control Methods

It is important to see the trend developed in sand control techniques in last few decades. The initial techniques were more concerned about stopping sand production, but recent studies have focused on maximizing oil productivity. It should be understood that both sand control and maximum productivity are important for successful sand control treatment.

1. Slotted pipe and Screens

Slotted pipe, perforated pipe, and screen by themselves or in conjunction with gravel packs, have been used for many years to stop movement of formation sands.

Early attempts to control sand production involved insertion of tubing perforated by drillled holes or torch cut slots. However, such devices had only limited success because the slot opening was not controlled. In

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the late 30's, Coberly published his classic work which led to improved designing of liner slot sizes. During the 1940's, efforts were made to determine the formation sand size and cut slots of a size which allowed sand particles to bridge the opening. The ten percentile grain size of the formation was commonly used as a representative grain size which, when bridged on a slot, would stop all sand entry into the liner. Slot sizes were commonly designed to equal twice the ten percentile particle diameter with the thought that this would bridge the sand on the slots. A slotting technique was developed that provided an under cut shape to the slots to allow a self cleaning action during fluids production to prevent slot plugging.

The first sand control screens were made by wrapping wire around drilled or slotted pipe. The wire was galvanized steel, copper, mild steel, and later, stainless steel. The advantage of screens was that the wire spacing could be made as small as necessary, whereas a slotted liner was limited to 0.03 inch wide slots as this was the smallest practical width of saw blade. Wire was keystone shaped to have the same self-cleaning action as the undercut slots. These screens were later improved by substituting weld beads by solder beads to add strength. This eliminated one of the previous design problems in which the wire was pulled off the pipe when the liner was pulled out of the hole. Another problem with early screen designs was reduced flow capacity as they were easily plugged with dirt. To increase the flow capacity of screens, ribs were positioned between the pipe body and the wire wrapping. This provided an increased flow area and reduced plugging tendency. The latest major development of screen manufacturing is the

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induction welding process which eliminates the weld head on the external surface of the screen. With this technique, a screen jacket is manufactured with the ribs and wire wrapping. This jacket can be used by itself for shallow wells or wherever the pipe base reinforcement is not required for strength. One of the major disadvantage of using screens or liners alone (in stead of gravel pack and liner completion) has been reportedly reduced productivity. When only a screen or liner is used, the formation sand grains must first move to the screen before they bridge or are stopped by the screen. This movement allows the sand grains to mix with themselves and any other clays or dirt present effectively reducing the wellbore permeability outside the screen.

2. Prepacked Screens:

A prepacked screen is one that uses sand or gravel along with the screen in order to be able to use a large slot opening and maintain higher productivity. Early designs were concentric slotted liners with gravel pack between the liners. Later designs used one slotted pipe with plastic consolidation gravel around it. Some screens had a ceramic like permeable matrix around the liner. A later design was concentric wire wrapped screens with plastic coated gravel between the screens. Even though prepacked screens appear to be more attractive than screens or liners, they are actually more susceptible to physical damage and plugging. The problem of having a low-permeability layer outiside the liner still exists just as for the screen or liner alone. Prepacked screens are also susceptible to be plugged while being lowered down the hole if the completion fluid is not very clean.

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3. Plastic Consolidation of Formation Sand:

In the late 1940's, the first attempts were made to strengthen formation sands by injecting unreacted plastic into the wells. This coated the sand grains and consolidated them as the plastic reacted to a hardened condition. This technique got wide acceptance in 1960's. However, its use is limited to short intervals of only 3 to 5 meters. Plastic consolidation is not effective for thicker formations.

4. Plastic Coated Gravel:

This technique was developed for use in wells that had already produced sand and in wells that required that no screen or liner remain inside of the wellbore. A slurry of unreacted plastic and gravel is pumped into a well and forced through the perforations until a "sandout" (filling of the annulus with sands) occurs. After the plastic has hardened, the excess plastic consolidated gravel is drilled out of the wellbore, and the treated wellbore is ready for production.

5. Conventional Gravel Packing:

This has been the most widely used sand control technique used over the years. This technique was adopted from water well technology and initially consisted of dumping sand or gravel down the annulus of a slotted pipe or screen. Gravel is designed to stop the movement of the formation sand, and the openings in the pipe or screen are designed to stop the gravel. The conventional gravel packing system simply adds gravel to water and pumps this blend into the wellbore around a screen or liner. Recent studies by Chevron Oilfield Research have shown that conventional gravel packing has the following deficiencies:

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- plugging of slots and wire wrapping by the gravel
- erosion occurring outside of port collars or crossover tools during gravel placement
- graduation of gravel sizes in the pack due to gravity segregation of grains
- difficulty in placing gravels in high angle holes

6. High Density Slurry Pack Technique:

This is presently the most widely used and successful sand control technique. It uses either a viscous oil or a gelled water to carry a high concentration of gravel into a well. The viscous carrying fluid carries the gravel through the perforations and packs it more tightly than the conventional gravel pack technique. There have been a few improvements over the original slurry pack technique. Frac packing, ultra-high gravel density, xanthan gum gelling agent, etc. have given improvements in recent years (Sparlin and Hagen, 1985).

7. Precoated Gravel:

This is a new system developed by Exxon research which uses a manufactured plastic precoated gravel. It is placed in a hole as in a gravel pack, but after the precoated gravel is in place, the plastic coating consolidates the gravel together.

8. Permeable Cement:

Several different types of permeable cements have been developed over the years by major oil company research centers, but none of these

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products have been commercially successful. Generally, they have failed due to sensitivity to water or acids.

9. Coking:

Sand consolidation by coking the crude oil was developed for heavy crude producing formations. Injection of hot air,gas, or steam at controlled rates into limited intervals will cause some crude oils to solidify around the sand grains and form a permeable, consolidated sand. This system has been successful in some areas, but it must be used in very short intervals, preferably in a single perforation or slot.

10. Permafix:

"Permafix" or "permaflow" were systems developed on the west Coast and later marketed in the Gulf Coast of the United states and in Canada. These systems were based on forming calcium hydroxide to consolidate the formation sand in place.The degree of consolidation was enhanced by the presence of clays and reasonably good strengths could be obtained in clayey formation sands, but poor strength in relatively clean sands. Although successes were reported from these treatments, the success ratio was low and the system has been a commercial failure.

11. New Generation of Screens and Filters

Recently, several liners and screens have been proposed. One of them is the Texaco Steel Wool liner which is a prepacked filter containing steel wool sandwiched between coarse steel cloths. This liner was designed and developed in Canada for wells for which harsh thermal

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conditions led to the failure of other sand control techniques. Even though there is some evidence of this prepacked filter being successful, similar problems as any prepacked screen are likely to occur. The commercial success of this filter has yet to be proven.

One other type of liner recently proposed is the flexible slotted liner and electric armor cables. They contain helical, complex shaped slots. Initial laboratory tests and a few unpublished field reports indicate mixed success of these liners. Research is yet to be performed on optimization of the shape and size of the slots.

Very recently, sand control with geotextile filters has been reported. Woven and nonwoven geotextiles have been developed as filters for underground drainage and water wells. This technology, combined with high technology textile, is applied to offer an improved sand control device.Feasibility of implementation of this type of filters is yet to be investigated.

1.5 Experimental Studies of Sand Production

There have been numerous studies of sand control in almost all laboratories of major oil companies and in service labs. However, very little work has been done to investigate the mechanism of sand flow and reasons of wellbore plugging.

Ayers (1965) is one of the very first researchers to discuss the stress field around a wellbore and its relation to the formation stability in terms of shear strength properties of the sand. Hall and Harrisberger (1970) extended this work to elucidate the failure mechanisms of unconsolidated sands and of the mechanism of stabilization

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of sands by consolidating plastics and to study arching behavior of sands. They used triaxial strength tests to show that low confining stresses resulted in a sharper failure indication than high confining stresses, and that grain crushing occurred in the high confining stress range. A small load (3500 kPa) improved arch stability in angular sand, while a large load(14000 kPa) led to arching failure due to grain crushing. Round sands failed to arch at all axial loads unless some restraint was induced on the grains by moistening the sand or flowing air through the opening. The authors determined Mohr-Coulomb failure envelopes for several sands. For unconsolidated sands, the failure line in this type is not a straight line. Curvature is caused by change in the way sand behaves at failure at different stress levels. The failure envelope is divided into three regions based on the dominating characteristics of failure.

Hall and Harrisberger (1970) also investigated effects of various saturation conditions on arch stability.They found that with stress conditions at which arches were unstable in either dry or saturated sand, arches would be stable if immiscible liquid phases were present and the wetting-phase saturation was less than fanicular. When wetting-phase saturation reached the fanicular state, the arches would fail. This observation was repeated for various combinations of fluids and reversal of the wetting relationship between the fluids. It was concluded that interfacial tension of a liquid-liquid-solid contact furnished a cohesive force which was necessary for arch stability. In their work, there was no consideration of measurement of effects of fluid flow rate or rate changes.

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Stein *et al.* (1972) provided theoretical techniques of estimating maximum sand free production rates from friable sands. Tippie and Kohlhaas (1973) described an investigation of fluid flow rate effect on arch formation and stability. The region near a perforation in a well completed in an unconsolidated sand reservoir was modelled with a semi-cylindrical sand pack confined in a test cell. Overburden pressure was applied with a diaphragm on top of the pack. For the arching tests, flow was started through the perforation at a low rate and after a short period of time, the initial arch examined. The cell was then reassembled and flow restarted at a low rate. Rate was gradually increased until sand was produced. They observed two ways in which arches will fail. In most cases, pressure drop across the sand would suddenly increase and large amount of sand would be produced. After a short period of time, sand-free production would be restored and pressure drop would be smaller than before sand was produced although the flow rate was kept constant. On the whole, they observed that flow rate is a factor determining arch size and stability and that manipulation of flow rate can have marked effect on producing characteristics of unconsolidated sand reservoirs. Smaller arches were found to be more stable and allowed a high fluid viscosity to be reached before failure. A gradual increase of rate permitted a higher sand-free production than a sudden increase to full rate.

Cleary *et al.* (1979) used a large cylindrical sand pack to study the stability of unconsolidated sands across casing perforations. Bottom hole producing conditions were simulated by various overburden stresses. Their experiments used irreducible water saturation and 20/40 frac

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sands. Visual observations were made by placing plexiglas viewing ports over the perforations. They observed that the arch structure is a function of the stress distribution in a sand pack. It was also observed that the shape of the sand arch depended on the direction of the principal stresses with arch size decreasing with increasing confining pressure. Kerosene and mineral spirits were used as the oil phases. Kerosene was found to exhibit stronger cohesive forces leading to a more stable arch than did the mineral spirits. Even though the absolute magnitude of cohesive forces is not very high, they have a large impact on dilatant restabilization of arches. Arch stability was found to increase with increasing horizontal and vertical stresses with the most stable arch being formed when horizontal stress was at the maximum and the vertical stress at the minimum.

Bratli and Risnes (1981) studied the arching phenomena occurring in unconsolidated sands under stresses due to fluid flow. They distinguished two modes of failure with increasing flow rates. First, a stable arch was formed followed by the collapse of thin inner shells to form new stable arches several times before total collapse and massive sand production. They also derived a stability criterion describing the total failure of the sand.

Selby and Farouq Ali (1988) studied the mechanics of sand flow into the wellbore. They used a radial flow model to simulate a wellbore. They reconfirmed some of the previous observations and established that sand production is affected by overburden pressure, the flow rate, and the size and shape of sand grains. They observed that sand production increases as the overburden pressure and fluid flow rates are increased.

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Arching of sands was enhanced by low overburden pressure, angularity of sand particles and low flow rates.

1.6 Mechanics of Sand Flow

Numerous studies have been conducted to investigate the mechanics of sand flow in wellbores. Gertsma (1957), Paslayand Cheatham (1963) are some of the earlier researchers who studied stresses around the wellbore induced by fluid flow. Gertsma (1957, 1978) has also studied other rock mechanical problems related to sand-free production.

Some of the earliest work done in estimating maximum sand-free production rate was conducted by Stein and Hilchie (1972). They presented a method for estimating formation strength from density and sonic logs. It involved assumptions that are correct as long as completion geometry is not substantially changed in different wells. This work was extended later on by Stein *et al.* (1974) for wells within dependent completion geometry. The technique was based on the assumption that the maximum possible pressure drop at the arch face for sand free production is proportional to the sand strength. That is, arch faces must remain in place if no sand production is to occur even if they are subjected to the maximum pressure gradient in the reservoir. Similar analysis was performed for sand-producing intervals in multi-completion gas wells (Stein *et al.*, 1972a). This work has later been extended for more competent sandstone formations (Tixier *et al.*, 1975, Stein, 1976). A log analysis technique for predicting formation strength based on elastic rock properties, an analysis of induced stresses in the rock, and a theory for rock failure was presented by Coates and Denoo (1980, 1981). This technique quantitatively relates

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draw down at the completion to induced stresses in the formation. A criterion for rock failure based on the maximum induced stress that the rock can withstand is then translated to the maximum draw down at which a formation may be produced prior to failure. Barrow and Lasseigne (1984) used the above mentioned technique to analyze eighteen offshore Gulf of Mexico wells.They compared the actual draw down at which sand production occurred with predicted formation failure draw downs. They concluded that the Mohr's Circle Technique would be a viable method for making sand control decisions.

Bratli and Risnes (1981) presented a theoretical method for predicting sand failure. A fundamental stability criterion describing the total failure of the sand was obtained by stress analyses of a simple spherical model. In this analysis, porous material was assumed to behave elastically until a Coulomb failure was reached in which the material would be in a plastic state. Expressions for the stresses were given for the elastic state and the plastic state. As discussed earlier, two modes of failure were detected by the model. The first one is the collapse of the inner shell, expressed by

$$\frac{\mu q}{4\pi k r_1} = \frac{T+1}{T}\, 4\, S_{co} \tan\theta \qquad (1)$$

and the total collapse is given by

$$\frac{\mu q}{4\pi k r_1} = \frac{T+1}{T}\, 4\, S_{co} \tan\theta \cdot \frac{1}{1 + \frac{1}{\theta}\left(\frac{r_1}{r_s}\right)^{T+1}} \qquad (2)$$

where μ is the fluid viscosity in Pa.s
q is the flow rate in m^3/s
k is the permeability in m^2

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T is the parameter depending on failure angle

θ is the failure angle

S is the cohesive strength in Pa

r_1 is the inner surface in m

r_s is the radius of the new arch at shell collapse in m.

Using similar analysis, Risnes *et al.* (1982) developed stability criterion for a wellbore. The stability criterion was given by

$$\frac{\mu q}{2\pi kh} = 2\, S_{co} \tan \theta \qquad (3)$$

where h is the height of the producing layer in m. As opposed to previous study, they eliminated the possibility of having inner shell collapse for constant-permeability wellbore. Inner shell collapse could be related only to a variable-permeability wellbore.

Stresses under thermal conditions were first studied by Reeves (1985). He argued that reservoir fluidization could occur due to high pore pressure during steam injection into unconsolidated reservoirs. He suggested that "pipes" or channels could be formed due this fluidization. He developed a theoretical model based on steady-state, non-Darcy flow in a homogeneous, isotropic porous medium. Vaziri (1988) investigated stresses present in oil sands.He developed a theoretical model in terms of elastic and thermal properties of multiphase soil systems. This finite element model gave a realistic predictions of reservoir performance.

1.7 Sand Cleaning Technique

Horizontal wells pose a particularly difficult problem of sand cleaning. For vertical wells, bailing of bottom hole sands is a routine

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task. However, this task is not trivial for horizontal wells. Cleaning sands through transport by means of carrier liquid appears to be an attractive alternative. Transportation of solids by means of a carrier liquid has been practiced industrially over a long period. In the U.S.A.and Europe, coal and minerals are already being transported in slurry form through pipelines several hundred kilometers long. The biggest problem with slurry transport is the tendency of solid particles to settle at the bottom of the horizontal section of the pipe. Consequently, estimates of the minimum velocity for particle transport has been a topic of research for long time.

Research on the transport of slurries in pipelines began in 1906's when Blach (1906) correlated pressure drop for sand slurries. Durand and Condolios (1952) were the first researcher to have reported on minimum velocity requirement for solid particle transport. They found that their results were independent of particle size for particles larger than 20 mm. Therefore, they looked for a parameter which would be dependent on particle size for small particles but less so for larger particles. They chose the drag coefficient, C_D, for the particle at its terminal falling condition and found that results for a wide range of particle sizes were correlated by incorporating $\sqrt{C_D}$ into the modified Froude number to give $\frac{V^2\sqrt{C_D}}{gD(s-1)}$. By carrying out a force balance at the terminal falling velocity one could obtain

$$C_D = \frac{2R'}{\rho V_o^2} = 4/3 \frac{d_g}{(s-1)V_o^2} \quad \text{for a sphere} \qquad (4)$$

$$= K \frac{d_g}{(s-1)V_o^2} \quad \text{for non-spherical particle of characteristic dimension d} \qquad (5)$$

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For small particles in the Stokes law region V_o is proportional to d^2 and C_D is dependent on particle size. For large particles, Newton's law region is applicable and V_o is proportional to $\sqrt{d}$ and C_D is independent of particle size.

Later on, Zandi and Govatos (1967) gathered a large number of published data to identify two separate regimes of slurry flow by using previous analysis by Durand and Condolios (1952). They derived correlating equations for the critical velocity for each of the two regimes. The equations involved pressure drop correlations, the pipe diameter, the drag coefficient, and the difference in the densities of the solid and the liquid. A theoretical expression for the minimum velocity of transport was derived by Oroskar and Turian (1980). Their analysis was based on the dynamic relationship between the turbulent energy and the forces tending to deposit the particles. Parzonka *et al.* (1981) reported, by studying published data, that the minimum velocity of transport attains a maximum value at around 15%.

Results for transportation of coarse solids have frequently been shown as $(\Delta P-\Delta P_w)/C\Delta P_w$ as a function of $\frac{v^2\sqrt{C_D}}{gD(s-1)}$. However, Chhabra and Richardson (1983,1985) showed that the assumption of $\Delta P-\Delta P_w$ being directly proportional to C for transportation with bed formation is no longer applicable for heterogeneous flow, even though the simplified model shows that it would be so. A better representation was suggested by incorporating C into the modified Froude number and plotting $(\Delta P-\Delta P_w)/\Delta P_w$ versus $\frac{v^2\sqrt{C_D}}{gD(s-1)}$. In all the above works, no account was taken either of the relative velocity of the liquid to the solids, or of the consequent differences between concentrations within the pipeline

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and in the mixtures. Khan *et al.* (1987) adapted similar procedure as Chhabra and Richardson. However, they expressed results as the difference between liquid and mixture velocity ($V_L - V_m$) as a function of mixture velocity V_m and in-line concentration C. They obtained a universal correlation by using the following equation:

$$V_L - V_m = 0.08\ V_m^{-0.64}\ C^{0.25}\ (ms^{-1})$$

Kim *et al.* (1986) presented an equation for calculation of the minimum velocity of transport of a slurry, using experimental data for the settling velocity of uniformly-sized particles, without having to measure the diameter of the particles. The results obtained with this proposed method were more accurate than any other reported correlation. They considered two different regimes, namely Stokes regime and intermediate regime. Critical velocities were estimated by the following expressions

For Stokes regime:

$$V_c = (1+AC^B)\ \frac{\sqrt{2}}{k}\ \left[\ 32\ \frac{g\mu\ (s-1)}{\rho}\ \right]^{0.25} (1-C)^{-0.25}\ U_c^{0.25} \qquad (6)$$

For intermediate regime:

$$V_c = (1+AC^B)\ \frac{\sqrt{2}}{k}\ \left[172.71\ \frac{g\mu\ (s-1)}{\rho}\ \right]^{0.1875} (1-C)^{-0.1875n}\ U_c^{-0.4375n} \qquad (7)$$

where A,B are constants

C is the concentration of slurry

k is the turbulent intensity, defined by $\sqrt{\overline{v^2}}/V$

$\overline{v^2}$ root-mean of time averaged square of velocity fluctuation

μ is the viscosity of the carrier fluid

s is the ratio of solid to liquid density

Uc is the velocity of sedimentation of a particle in a suspension

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ρ is the density of liquid

n is the flow index

These equations can be used in the following Durand formula to obtain pressure drop values.

$$\frac{\Delta P - \Delta P_w}{\Delta P_w C} = 280 \left(\frac{V^2}{gD(s-1)} \right)^{-1.5} \quad (8)$$

While the above analysis is important in order to determine sand transport capability of the flowing fluid, it is likely that sand deposited in a horizontal well cannot be transported by flowing fluids alone. Conequently, a fluid may be used as a jet in order to create tubulent flow in the wellbore. Performance of such a fluid can be predicted by using existing slurry flow models. One such model is chosen for the present study.

2.0 EXPERIMENTAL DESIGN AND PROCEDURE

Recently several authors have reported laboratory test of sand control devices (Selby and Farouq Ali, 1988; Toma *et al.*, 1986). Experimental design for their equipment was consistent with those used by previous researchers (Hall and Harrisberger, 1970; Tippie and Kohlhaas, 1973; Cleary *et al.*, 1979) who tested primarily shear resistance of sands under various confining pressures and observed collapse in arching as a function of flow rate, confining pressure, etc.

In the present study, the top one-eighth of horizontal well was modeled. Figure 1 shows the schematic diagram of the experimental set-up. The flow area on which the sand control device was lodged in the core holder represented one-eighth of a horizontal tubing with a length

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of 3 cm and diameter of 13 cm. This diameter is considered to be typical in horizontal wells in heavy oil reservoirs. Two jet openings were installed in order to be able to inject cleaning fluid at high flow rate in case of sand plugging. In order to simulate the field situation for which there is a gap between slotted liner and the formation sand, a specially designed liner combination was devised. In this combination, the outer layer was formed by a 0.025" (0.0635 cm) wire-wrapped screen and was designed to provide mechanical support to the overlying formation without stopping sand flow. This outer liner was chosen after initial tests indicated unrestricted sand flow with a 0.025" liner. This outer layer will be called the 'casing liner'. The actual sand control screen was placed inside keeping a gap of 2.54 cm between the outer and inner screens. The inner screen will be called the 'tubing liner'. As a result of fluid flow,the chamber between the two layers was filled up with intermixed sand particles creating a "low permeability" layer between the sand control screen and the formation sand face. The existence of such a "low permeability layer" between the liner and the formation is believed to exist in the field where a liner is placed directly in the formation without gravel packing.

A sand pack of the formation sand to be tested was placed on top of the liner assembly and was surrounded by a rubber sleeve to which an external pressure could be applied using nitrogen. Pressure could be exerted equally from the top of the core through a piston which could travel along the sleeve in order to maintain a constant overburden pressure even when sand particles were being produced in high concentration. The test cell was connected to injection and production

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inlet/outlets. Pore volume was measured for each run by pulling vacuum in the cell and resaturating with brine. For each experimental run, pressure drop was measured with brine at the beginning of the run. A considerable amount of brine was injected in order to fill up the chamber between casing and tubing liners. Pressure drop was measured throughout to estimate any drop in permeability due to rearrangement of sand particles in the vicinity of the tubing liners. Subsequent to water flow, an oil flood, followed by a waterflood, was carried out. Several flow rates were used (increasingly higher) for the oil flood and the waterflood. Consequently, sand entrainment could be noted as a function of oil type, oil viscosity, flow rate, producing water-oil ratio, as well as liner type. After each run, the amount and particle size distribution of produced sand (if any) and trapped sand (in the chamber between casing and tubing liners) were measured. The amount of sand produced along with pressure data was used as the criterion for liner performance.

Figure 2 shows the experimental set-up for helical tubing experiments. For this series of runs, no overburden pressure was applied Flexible liners of diameter 1" could be tested in this equipment. Only water injection was carried out in this series of experiments. Samples of produced water were collected to obtain volume of sand produced. The fluid injection/production system was automated. These liners were supplied by Tift Inc.

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2.1 Selection of 'Tubing Liner'

In order to determine which openigs should be selected for 'tubing liners', contacts were made with Husky Oil Ltd. and Site Oil Tools personnels. Wire-wrapped screens were found to be most widely used liners in heavy oil reservoirs of Lloydminster. Initial selection of wire-wrapped screen openings was made from the knowledge of the liners used for vertical wells. For vertical wells in thermal or non-thermal productions, the most widely used wire-wrapped screens are of openings of 0.010", 0.012" and, occasionally, 0.018". Therefore, these were the openings selected for the present experimental investigation.

3.0 RESULTS AND DISCUSSION

3.1 Presentation of Experimental Results:

In this study, two types of experimental tests were carried out. One of them was to test wire-wrapped screens, the other one was to test flexible helical tubings. Three different sand samples were used. They were Tangleflags, Aberfeldy, and Pikes Peak reservoir sands. All these reservoirs are heavy oil reservoirs with different degrees of sanding problems. Tangleflags and Aberfeldy are known to have sanding problems. Wells in these reservoirs are equipped with sand control devices. On the other hand, the Pikes Peak production team has adopted the philosophy of unrestrained sand production. The production rate in this reservoir is believed to be enough to lift sand from the reservoir to the surface level (Carlson, 1988). The sand samples were chosen such that a wide range of sanding performance is covered.

Table 1 contains characteristics of the experimental runs. For Runs 1 through 14, the amounts of oil, water, and sand were measured in order

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to obtain any correlation between water-oil cut with sand production. However, for each run steady state was established with brine before oil flood was initiated. This was followed by a waterflood. For the series of runs using flexible liner, experiments were limited to continuous water injection. These runs were conducted by injecting water at different flow rates. For each flow rate chosen, water injection was continued for an hour after which sand remaining in the horizontal liner was removed and weighed.

3.1.1 Characteristics of Sands

Figure 3 shows the particle size distribution for three different sand samples used in various experiments. D_{10} (sieve size which will allow 90% of the samples to pass through) values dictate that 0.008", 0.010", and 0.012" liners should be used for Aberfeldy, Tangleflags, and Pikes Peak, respectively in the case of liner only completion. On the other hand, if a gravel pack was to be implemented, using Swartz criteria, the finest gravels would have to be used for Pikes Peak, followed by Aberfeldy and then Tangleflags. Scanning electron microscope (SEM) photographs of the sand samples are shown in Figure 4. Fines contents of various sands were different. In addition, for one of the runs (0.018" Aberfeldy sands and 12,500 mPa.s oil), SEM photomicrographs were taken after being produced in the flow cell under overburden pressure of 1000 kPa. This microphotograph along with particle size distribution plots showed that a considerable shift in particle size occurred. This indicated that larger particles were trapped whereas finer particles continued to be produced. This analysis could not be done for smaller

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opening wire-wrapped screens since the volume of produced sand was too small for SEM and particle size analyses.

3.1.2 Characteristics of Fluids:

Characteristics of the oils used is given in Table 2. They were collected from produced fluids in the field of Aberfeldy and Pikes Peak. In order to have a range of viscosities, crude oil samples were blended with solvents. Acid number is a measure of the acidic constituents that are present in the oil. Acid number was measured using ASTM D664-81 method. Viscosities were measured using Brookfield model LVTDV viscometer. Among others, Carboxyl IR peaks were measured on a Perkin Elmer model. Three different oils were selected for oil flood tests. They were a blend of crude oils with viscosities of 1000, 8400 and 12500 mPa.s. Even though oils were chosen to study the effect of oil viscosity on sand particle entrainment, they also differed in some other characteristics. This could not be avoided since crude oils were chosen from corresponding oil reservoirs.

A 2% brine solution was used to simulate reservoir water for all the runs. The same brine solution was used for waterflood runs.

3.2 Discussion of Results

3.2.1 *Sand Arching and Stability:*

Run 1 was conducted to investigate sand arch stability as a function of flow rate. For this run, a 0.025" liner was used. As can be seen in Figure 5, a 0.025" liner should not stop sand production as this opening is equivalent to an opening which will allow passage of almost 100% sand. However, wet sand is likely to form arches due to cohesive forces. While these cohesive forces are unlikely to be enough to form stable

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arches, Figure 5 indicates that cohesive forces do contribute to partial stability so that sand production decreases considerably. Flow rates used for this run were 100, 200, 300, and 400 ml/hr. These values correspond to field values of 0.178, 0.356, 0.712, and 1.424 m3/day/m of the horizontal well. Figure 5 reveals two aspects:

- sand arching is quicker for higher flow rates in a horizontal well and sand production is minimal

- initial sand production is the highest for high flow rates.

This observation leads to an important production strategy for horizontal wells. Unlike vertical wells, low fluid production rates do not mean low sand production. A higher production rate may lead to better stability at least for flow through the top of the horizontal well. This behavior for horizontal wells is equivalent to vertical well performance under zero overburden pressure. However, this figure also indicates how easily a horizontal well may be plugged. By scaling up the sand production data, one can see that sand production is as high as 180 kg/day/m of horizontal well. Even though this high sand production should drop considerably within a few months of production, this result is only meaningful when sand is constantly being removed from the wellbore. This obviously is a problem in a horizontal well. Consequently, an effective sand control technique must be implemented.

Another piece of information derived from Run 1 was related to creating a mechanical support for the sand pack above the 'tubing liner'. Since the 0.025" liner showed continuous sand production, it was decided to use this liner as a support in the outer boundary (called

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casing liner). The idea was to simulate the annulus of a horizontal well for which a liner is inserted directly into the sand formation leaving a gap between the liner and sand face.

3.2.2 Effect of Screen Opening for Aberfeldy Sand and Oil Viscosity of 12,500 mPa.s

Runs 3, 4, and 5 were conducted to investigate the effect of wire-wrapped screen opening on sand production behavior for Aberfeldy sands using 12,500 mPa.s crude oil. Screen openings of 0.018", 0.012", and 0.010" were used for Runs 3, 4, and 5, respectively. Figures 6 through 8 show the WOR and sand production data for these runs. During initial stabilization (filling of the annulus) with water, a lot of sand was produced. Even though higher production rate decreased sand production considerably, this sand production rate is not acceptable since scaled up sand production values are too large and sand plugging of the well itself is very likely to occur. Similar to what was observed with water injection (initial stabilization period), increasing flow rate decreased sand production rate. This can be seen from Figure 6. However, even at high fluid flow rate sand production was high (5 kg/day/m of the horizontal well) enough to plug a horizontal well.

On the other hand, a smaller amount of sand was produced when a 0.012" liner was used (see Figure 7). During two-phase flow, sand production appeared to decline as the test continued. No correlation between WOR and sand production was evident in this case. The liner of 0.010" opening produced even less sand (see Figure 8). For this particular case, sand production fluctuated around 0.01 g/min. This value is very similar to that of 0.012" liner leading to the conclusion that with the sand/fluid

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system, a change from 0.010" to 0.012" does not contribute much in creating stable arches. However, the initial sand production rate was substantially less for 0.010" liner. For all these cases, sand production occurred mostly at initial stages of water saturation when sands were being redistributed into the annulus. Water injection at this stage was carried out at increasingly higher rates. Even though injection pressure increased proportional to the flow rates, sand production decreased to negligible amount with increasing flow rates. While this observation confirms the finding of Run 1, data acquired in these runs are not enough to lead to a quantitative evaluation.

Trapped sands in the chamber between 'casing liner' and 'tubing liner' were collected and particle size distributions were determined. Figure 9 shows particle size distribution for sand trapped by 0.010", 0.012", and 0.018" liners. This figure indicates that particle size distribution for 0.018" liner is least affected although the sand trapped in the annulus is finer than that in the core. Liners 0.010" and 0.012" trapped a larger fraction of finer particles. This is consistent with the fact that most permeability damage in the annular space (due to particle redistribution) occurred for 0.01" liner. Low permeability in the annulus is a matter of great concern. Permeability damage due to the annular particle redistributions is reported in Table 3.

3.2.3 Effect of Screen Opening for Aberfeldy Sand and Oil Viscosity of 8,400 mPa.s

Runs 6 and 7 were conducted using 0.010" and 0.012" wire-wrapped screens, respectively. For both these runs, blended crude oil of viscosity 8,400 mPa.s was used. Water-oil ratios and sand production

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results are depicted in Figures 10 and 11. Much of the sand was produced during initial water injection. Increasing production rates decreased sand production. This is consistent with previous observations. However, sand production during two phase flow appeared to have followed a different pattern than that of previous runs (with higher oil viscosity). Quantitative values of sand production are similar but sand production rate appears to be more stabilized (steady) for this series of runs.

Sands trapped in the chamber between 'casing liner' and 'tubing liner' were analyzed for particle size distribution. Figure 12 shows the particle size distributions for Runs 6 and 7. Comparing this figure with Figure 9 it appears that slightly finer particles are trapped in this case. As can be seen in Table 3, permeability reduction factors were 2.9 and 2.6 for liners 0.010" and 0.012", respectively.

3.2.4. Effect of Screen Opening for Aberfeldy Sand and Oil Viscosity of 1,000 mPa.s

Runs 8 and 9 were conducted using 0.012" and 0.010" wire-wrapped screen, respectively. For these runs an upgraded crude oil from Aberfeldy reservoir was used. The viscosity of this upgraded oil was 1000 mPa.s. Water-oil ratios and sand production rates for these runs are shown in Figures 13 and 14. Similar to what was observed in previous runs, most of the sand production with both screens took place during water saturation of the model. The trend of having steady sand production is more evident for these runs during two-phase flow. With increasingly lower viscosity oil, stable arches do not form very well.

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Sand particles trapped between tubing liner and casing liner were analyzed. The particle size distribution for these runs are plotted in Figure 15. When they are compared with previous runs with higher oil viscosity it appears that finer particles are trapped in the case of lower oil viscosity. Consequence of this behavior is the loss of permeability in the annulus and continuing sand production with even smaller screen size (0.010"). Because the screen 'sees' finer sands in the annulus, the liner selection which is based on the analysis of the formation sand is no longer valid. The reason that lower viscosity oil traps more fine particles in the annulus may be as follows:

Cohesive forces (being dependent mainly on the surface tension of the fluid filling the void between solid particles) will be similar for all three oils which have similar surface tensions. (Schubert, 1979). However, drag forces being dependent on oil viscosities will differ being much stronger for higher viscosity oils. As a consequence, higher viscosity oils are more likely to break the cohesive forces between the sand particles and drag them through the casing liner. Lower oil viscosity will mobilize fines selectively but may not break sand arches across the screen openings so readiliy. Consequently, the annular space is not swept clean of fine particles for lower oil viscosity cases.

Initial permeability reductions due to sand particle redistribution during water saturation are reported in Table 3. Permeability at the end of the whole test was not measured since no comparable end point was attained in the various runs. However, due to finer particles being trapped in the chamber, it is likely that the low viscosity runs will

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suffer the most permeability damage.

3.2.5 Effect of Screen Opening for Tangleflags Sand and Oil Viscosity of 8400 mPa.s

Runs 2, 10, and 11 were conducted using Tangleflags sand and an oil viscosity of 8400 mPa.s. For Run 2, sand was packed directly on top of the 0.010" wire-wrapped screen. Regular two-liner packing was used for Run 10 and 11 with tubing liner size of 0.012" and 0.010", respectively. This gave an opportunity to observe the effect of annular space on sand production results. Water-oil ratios and sand production rates are depicted in Figures 16 through 18. A comparison between Run 2 and 11 shows that by placing the liner directly against the sand face, sand production is reduced, especially at high fluid flow rates. This is likely to happen because the sand particles encountered by the 'tubing liner' are finer than the ones encountered by the liner in direct contact with the sand face. Direct contact with formation sand also means no permeability damage due to the formation of a low-permeability sand packed annulus. Furhter, stable arches are formed more effectively for the direct contact case as is evidenced from the slope of the sand production curve in Figures 16 and 18. Permeability reductions for Runs 10 and 11 are similar to what was observed for previous runs. More damage occurred for lower screen opening case. These values are reported in Table 3. Figure 19 shows the particle size distributions of trapped sands for these runs.

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3.2.6 Effect of Screen Opening for Pikes Peak Sand and Oil Viscosity of 12500 mPa.s

Runs 12 and 13 were conducted with Pikes Peak sand and oil viscosity of 12500 mPa.s. Wire-wrapped screen openings of 0.018" and 0.012" were used for Runs 12 and 13, respectively. Figures 20 and 21 show water-oil ratio and sand production curves for these runs. When scaled up to field production, the sand production rate with 0.018" becomes unacceptable for horizontal wells. Figure 22 compares particle size distributions for these runs. It appears that finer sands are trapped for 0.012" leading to higher permeability damage. However, sand production is considerably lower for 0.012" screen. Initial permeability loss values are reported in Table 3.

3.2.7 Effect of Screen Opening for Pikes Peak Sand and Oil Viscosity of 1000 mPa.s

Runs 14 and 15 were conducted using Pikes Peak sand and 1000 mPa.s viscosity oil. Wire-wrapped screen opening of 0.018" and 0.012" were used for Runs 14 and 15, respectively. Figures 23 and 24 show sand production and water-oil ratio as a function of time for these runs. Extrapolated field results show that 0.018" screen is unacceptable due to high deposit of sand particles. Figure 25 shows particle size distribution of trapped sands for these runs. A comparison of these results with those obtained in high-viscosity runs indicate that finer particles were trapped in higher quantity for these runs. A similar result was obtained in previous runs with low oil viscosity. This observation confirms the previous postulation that low viscosity oil will

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lead to the entrapment of finer particles in the gap between formation and liner. Initial permeability loss due to sand particle redistribution in the annular space is reported in Table 3. Due to entrapment of finer particle in the presence of 0.012" wire-wrapped screen, permeability damage is higher for Run 15. Again, this observation is consistent with previous runs.

3.2.8 Effect of Flow Rates:

For all the runs, after initial stabilization (filling of the chamber between casing and tubing liner), water injection rate was doubled in order to observe the effect of flow rate on sand production. As could be seen in the slope of the sand production curves, high flow rate consistently decreased sand production in all the cases. A similar trend has been observed for the case of vertical well with no overburden pressure (Selby and Farouq Ali, 1988). During two-phase flow, waterflood rate was doubled in some of the runs and a similar effect on sand production was observed. We conclude that the presence of gravitational forces colinear with flow direction led to more stable arches for the case tested here. Increasing inertial forces (due to high flow rate) enhances this phenomenon.

3.2.9 Effect of Annulus Space On Overall Permeability Damage

Taking the initial permeability damage observed for various cases, calculations were made to estimate the effect of annular space on overall permeability damage. This is shown in Figure 26 as a function of annular space and reservoir thickness for the Aberfeldy sand and 0.010" liner. Of course, for thicker reservoirs the impact of the annular space becomes smaller. However, for thinner reservoirs (which is the case in

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Canadian heavy oil reservoirs), a large annular space may cause significant damage.

3.3 Flexible Liner Results

Flexible liners were tested for all three reservoir sands and water. Three different liners were tested. Only one set gave satisfactory results with all the sands. Runs 16 through 18 were conducted using Pikes Peak, Aberfeldy, and Tangleflags sand samples, respectively. Sand production in all the runs was limited to a very small amount. In fact, sand production in Run 18 was so small that the amount could not be measured with the present measuring device. Sand production data for Runs 16 and 17 are depicted in Figures 27 and 28, respectively. Pressure drop across the screen was minimal (observed stable pressure drop during water injection at various flow rates) and no plugging was observed. The best performance was observed when flexible liners were half-way extended. A fully extended or fully retracted liner created permanent blockage of flow. After each run, the screen was pulled apart to observe if any sand particle was trapped inside the liner spacing. Very little sand was trapped. Bridging formed against the outer opening prevented any sand from entering the passage through the liner. Consequently, no permeability damage occurred during fluid flow. Figure 27 and 28 show that sand production again decreased with increasing flow rate across the liner. A high flow rate enhances bridging around the liner and prevents sand from entering the open spacing.

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3.4 Sand Deposit During Fluid Flow

As can be seen in field sand production performance for various liners, it is very likely that some of the liners will allow so much sand production that the well will be plugged very quickly. The portion of liners which will be filled within a day or so is calculated for various wire-wrapped screens using stabilized sand production rates. Figure 29 and 30 depicts the nature of sand deposit in a 7" liner for Aberfeldy, Pikes Peak and Tangleflags sands and various oil viscosities. Even though the nature of sand production varies with oil viscosity, it is very clear that sand production is too high for 0.018" wire-wrapped screens and the amount of sand deposited indicate that even with high oil viscosity, sand will not propagate in laminar flow regime (which is usually the case in heavy oil reservoirs).

3.5 Cleaning Horizontal Wells

Horizontal wells pose a particularly difficult problem of sand cleaning. As observed in experimental runs, even a small amount of sand production through screens may accumulate to create plugging in a horizontal well. Cleaning sands through transport by means of carrier liquid appears to be an attractive alternative. However, flow rates near wellbore in laminar flow may not be high enough to transport solid particles along the length of the horizontal well. In order to predict particle transport behavior for various fluid viscosities, a two-layer model (Shook *et al.*, 1986) was employed. Figure 31 shows the hypothetical two-layer mixture. The model employs mass and force balance equations for the flow depicted in Figure 31. The hypothetical

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horizontal interface separates the particle free upper layer from the lower layer of concentration C_2. The mass balance for the total slurry is given by:

$$A\,V = A_1\,V_1 + A_2\,V_2 \tag{9}$$

Force balance equations for each layer are coupled through the stress on the interface. For steady flow:

$$\Delta P \rho_f g = (\tau_1 S_1 + \tau_{12}\,S_{12})/A_1 \tag{10}$$

$$\Delta P \rho_f g = (\tau_2 S_2 - \tau_{12}\,S_{12})/A_2 \tag{11}$$

Initially, a value for the lower layer concentration, C_2 is assumed. Next, the value of C_c, the contact load, is obtained. In order to do that, a correlation suggested by Shook *et al.* (1986) was used. It is give by:

$$\frac{C_c}{C} = \exp\left[\,-0.124\,Ar^{-0.061}\,F_r^{0.028}\,(D/d)^{0.431}\,(S_s-1)^{-0.272}\,\right] \tag{12}$$

where Ar, F_r , and S_s are Archimedes number, Froude number, and particle/fluid density ratio, respectively. From C_c, the suspended load C_1 can be determined from the following relationship.

$$C_1 = C_r - C_c \tag{13}$$

From C_1 and C_c values, the area A_2 can be calculated.

$$A_2 = A\,C_c/(C_2 - C_1) \tag{14}$$

Knowing A_2, the angle β can be calculated iteratively by the following relationship:

$$A_2 = D^2\,(\beta - \sin\beta\cos\beta)/4 \tag{15}$$

From geometrical consideration, one obtains

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$$A_1 = A - A_2 \tag{16}$$

$$S_1 = D\,(\pi - \beta) \tag{17}$$

$$S_2 = D\,\beta \tag{18}$$

$$S_{12} = D \sin \beta \tag{19}$$

Equations 9, 10, and 11 are solved iteratively for the unknown variables V_1, V_2, and ΔP. Selection of correct V_1 will result in a pressure drop from Equation 10 by using Equation 11. As a starting point, V_1 is assumed to be equal to V. V_2 is then calculated from the Equation 9. The stresses are calculated as follows:

$$\tau_1 = f_1\, V_1\, |V_1| \rho_1/2 \tag{20}$$

$$f_1 = f_1\,(Re_1,\ \epsilon/D) \tag{21}$$

Churchill's (1977) equation is used to calculate f_1:

$$f_1 = 2\,[\,(8/Re_1)^{12} + (a+b)^{-3/2}\,]^{1/12} \tag{22}$$

$$a = \left(2.457 \ln \frac{1}{\left[\frac{7}{Re_1}\right]^{0.9} + \frac{0.27}{D}} \right)^{16} \tag{23}$$

$$b = (37530/Re_1)^{16} \tag{24}$$

$$\text{And,} \quad Re_1 = \rho_1\, DV/\mu_1 \tag{25}$$

For low solid concentration, $\mu_1 = \mu_f$. Stress τ_{12} depends on the particle diameter and the difference in velocity between layers:

$$\tau_{12} = f_{12}\,(V_1 - V_2)\,|V_1 - V_2|\,\rho/2 \tag{26}$$

Stress τ_2 includes two effects: fluid-wall friction in the lower layer and particle wall sliding friction. Neglecting transmission of stress τ_{12} through the lower layer and considering the effects of buoyancy

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produced by suspended particles in the lower layer:

$$\tau_s S_2 = (f_2 V_2 |V_2| \rho_1 S_2)/2 + [(\rho_s - \rho_2) g D^2 \eta_s (C_2 - C_1)(\sin\beta - \beta\cos\beta)]/2 \quad (27)$$

In the above formulation, η is the coefficient of kinematic friction and is reported to be 0.5 by Shook *et al.*(1986).

The density of the suspended mixture in the lower layer is:

$$\rho_2 = [C_1 \rho_s + (1-C_2)\rho_f]/(1 - C_2 + C_1) \quad (28)$$

3.4.1. Results of Mathematical Modelling:

The above mentioned equations were solved numerically to obtain the pressure drop per metre of a horizontal well of diameter 5 inches. Viscosity of the carrying fluid was assumed to be 1.0 mPa.s. (a cleaning fluid different from produced oil may be used in a horizontal well system) Figure 32 shows the pressure drop along the length of the horizontal well for various sand concentrations. As can be seen in this figure, sand concentration increases pressure drop quite dramatically. Note that the pressure drop reported in the figure is for each metre. For a long horizontal well, the overall pressure drop may be very high leading to an unrealistic injection pressure requirement (for cleaning fluid) at the end of the horizontal well.

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4.0 CONCLUSIONS:

Based on results obtained in this study, the following conclusions were reached:

- wire-wrapped screens of 0.010" opening were proven to be the most effective among liners tested (0.010", 0.012", 0.018", 0.025") with sands from Aberfeldy, Pikes Peak, and Tangleflags reservoirs.
- permeability damage due to particle redistribution was quantified and was found to increase with decreasing screen opening and oil viscosity.
- overburden pressure helped minimize sand production for the case of production through the top of a horizontal well.
- flexible liners were found to be the most effective in controlling sand
- inertial forces helped reduce sand production for all sand control device tested.
- a numerical slurry flow model was developed in order to predict pressure requirements for a cleaning liquid in a horizontal well. An extremely high pressure drop was predicted for the case of high sand concentration in the horizontal well.

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6.0 TABLES

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TABLE 1: Characteristics of Different Runs

Run no.	Sand Used	Liner Used	Oil Viscosity (mPa.s)
1.*	Tangleflags	0.025"	N.A.
2.*	Tangleflags	0.010"	8,400
3.	Aberfeldy	0.018"	12,500
4.	Aberfeldy	0.012"	12,500
5.	Aberfeldy	0.010"	12,500
6.	Aberfeldy	0.012"	8,400
7.	Aberfeldy	0.010"	8,400
8.	Aberfeldy	0.012"	1,030
9.	Aberfeldy	0.010"	1,030
10.	Tangleflags	0.012"	8,400
11.	Tangleflags	0.010"	8,400
12.	Pikes Peak	0.018"	12,500
13.	Pikes Peak	0.012"	12,500
14.	Pikes Peak	0.018"	1,030
15.	Pikes Peak	0.012"	1,030
16.	Pikes Peak	Flexible	N.A.
17.	Aberfeldy	Flexible	N.A.
18.	Tangleflags	Flexible	N.A.

N.A. Not applicable (Run conducted with water only)

*Runs conducted with sand control screen directly in contact with the sand face

TABLE 2. Properties of Oils Used

Oil Sample no.	Viscosity (mPa.s)	Acid number mg KOH/g	Density g/ml
1.	1030	0.925	0.89
2.	8400	0.905	0.91
3.	12500	0.625	0.90

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TABLE 3. Permeability Damage in the Annulus

Run no.	Annulus Permeability/Core Permeability
3	1.8
4	2.7
5	3.1
6	2.6
7	2.9
8	2.4
9	2.9
10	1.9
11	2.4
12	1.9
13	2.2
14	1.8
15	2.0

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8. FIGURES

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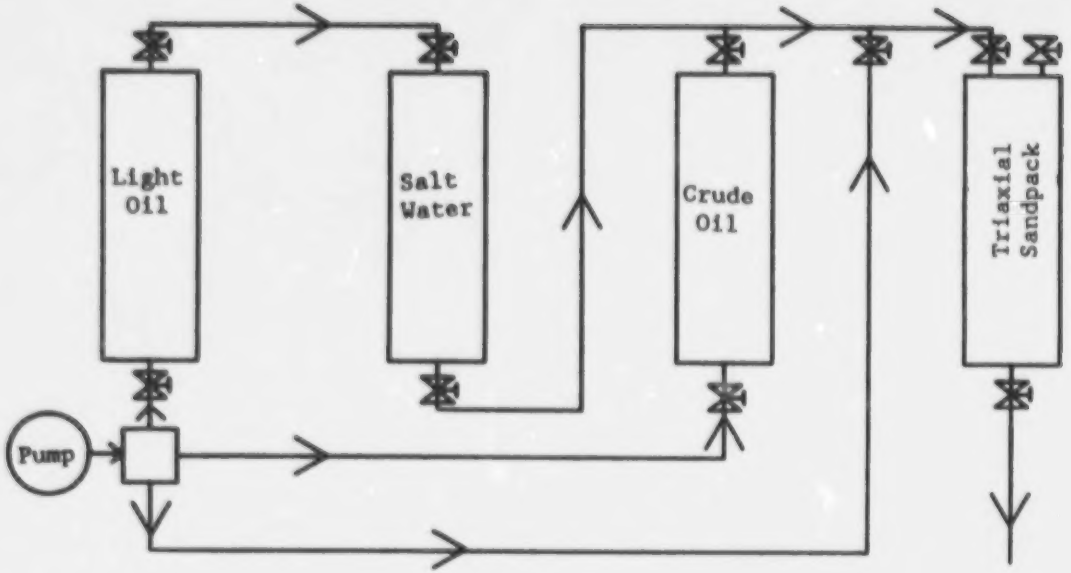

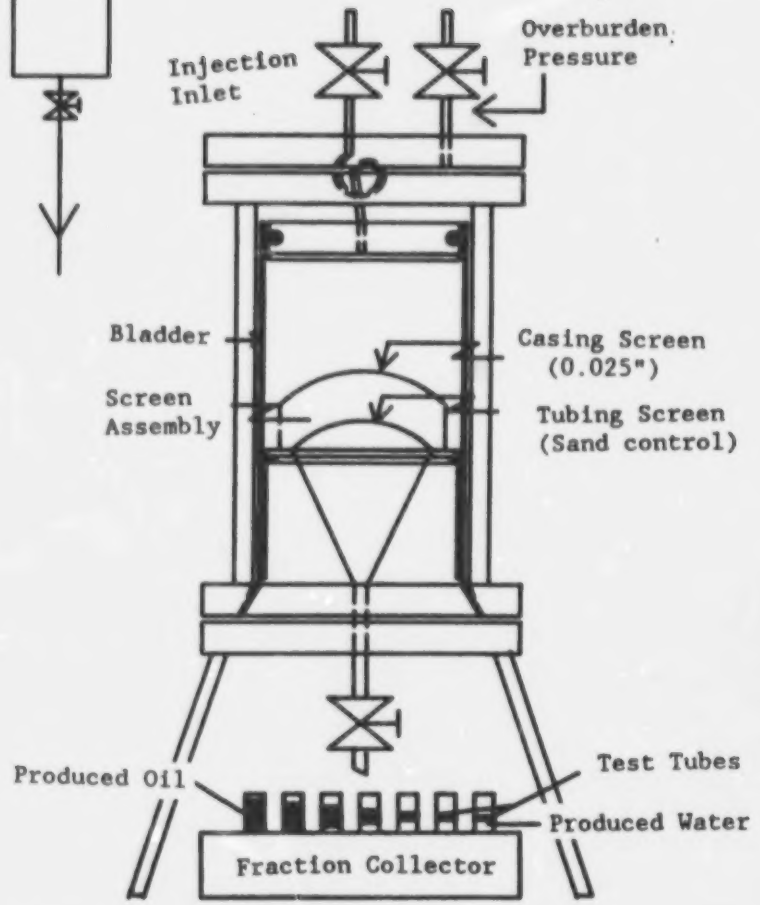

Figure 1. Experimental Set-up for Wire-wrapped screen tests

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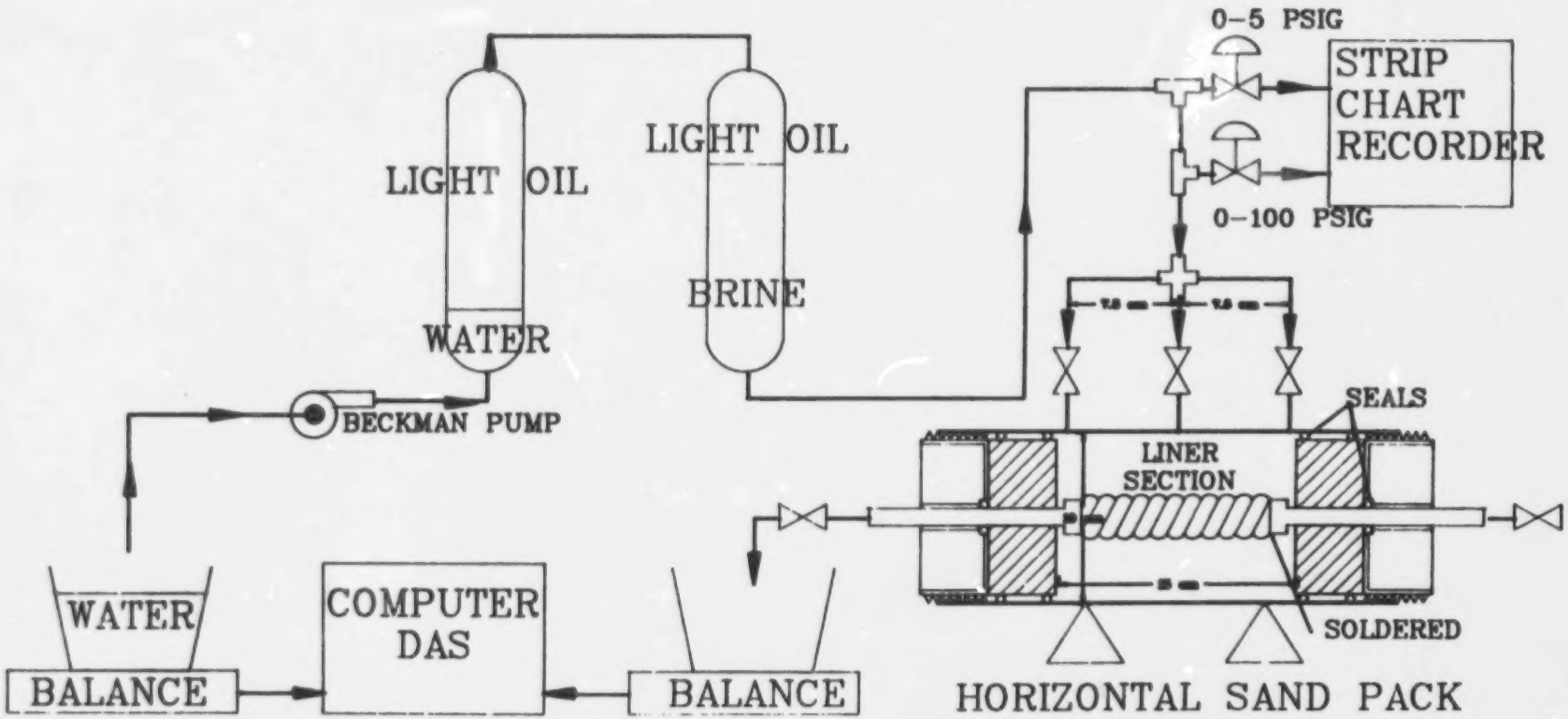

Figure 2. Experimental Set-up for Flexible liners

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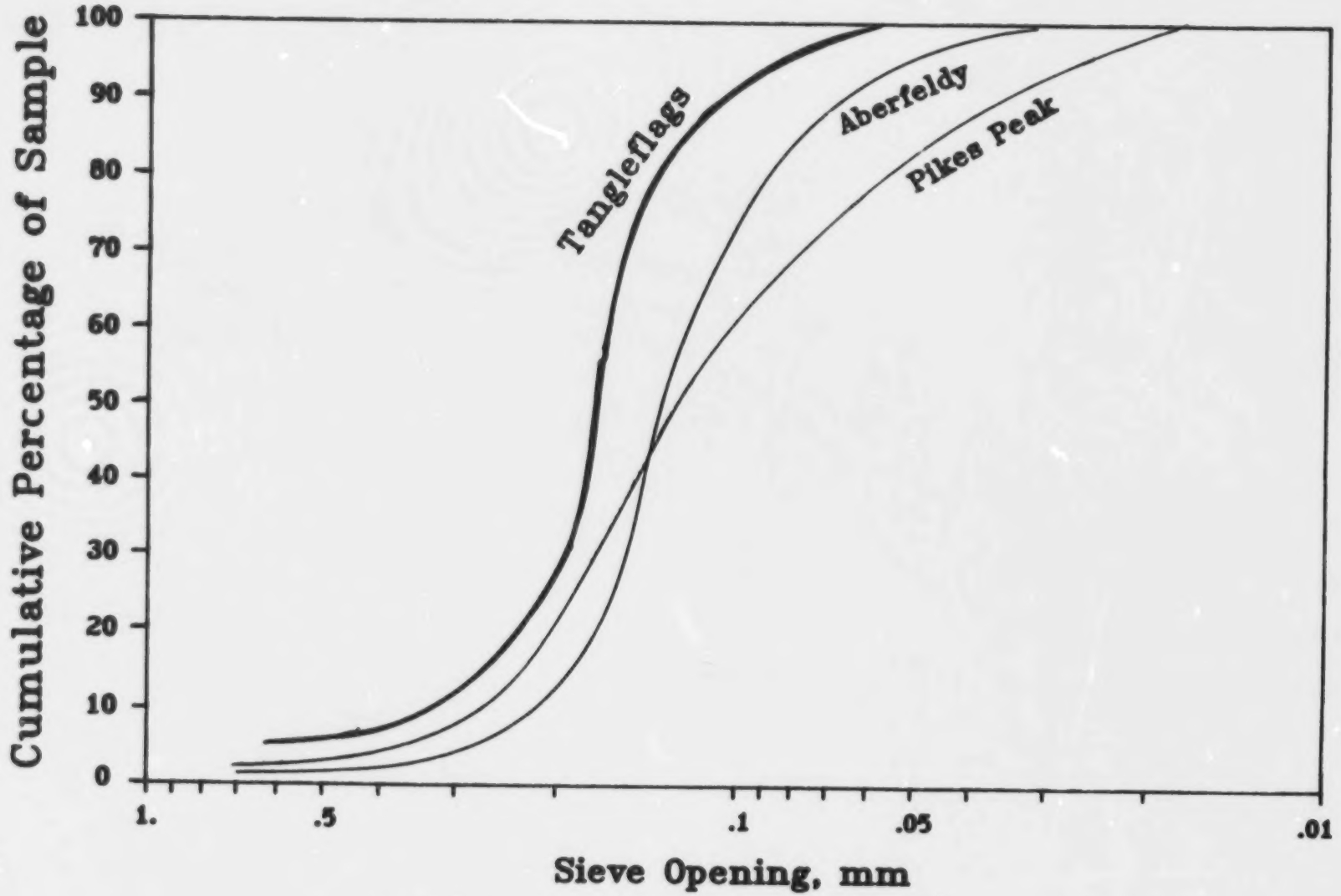

Figure 3. Particle Size Distribution for Different Sands

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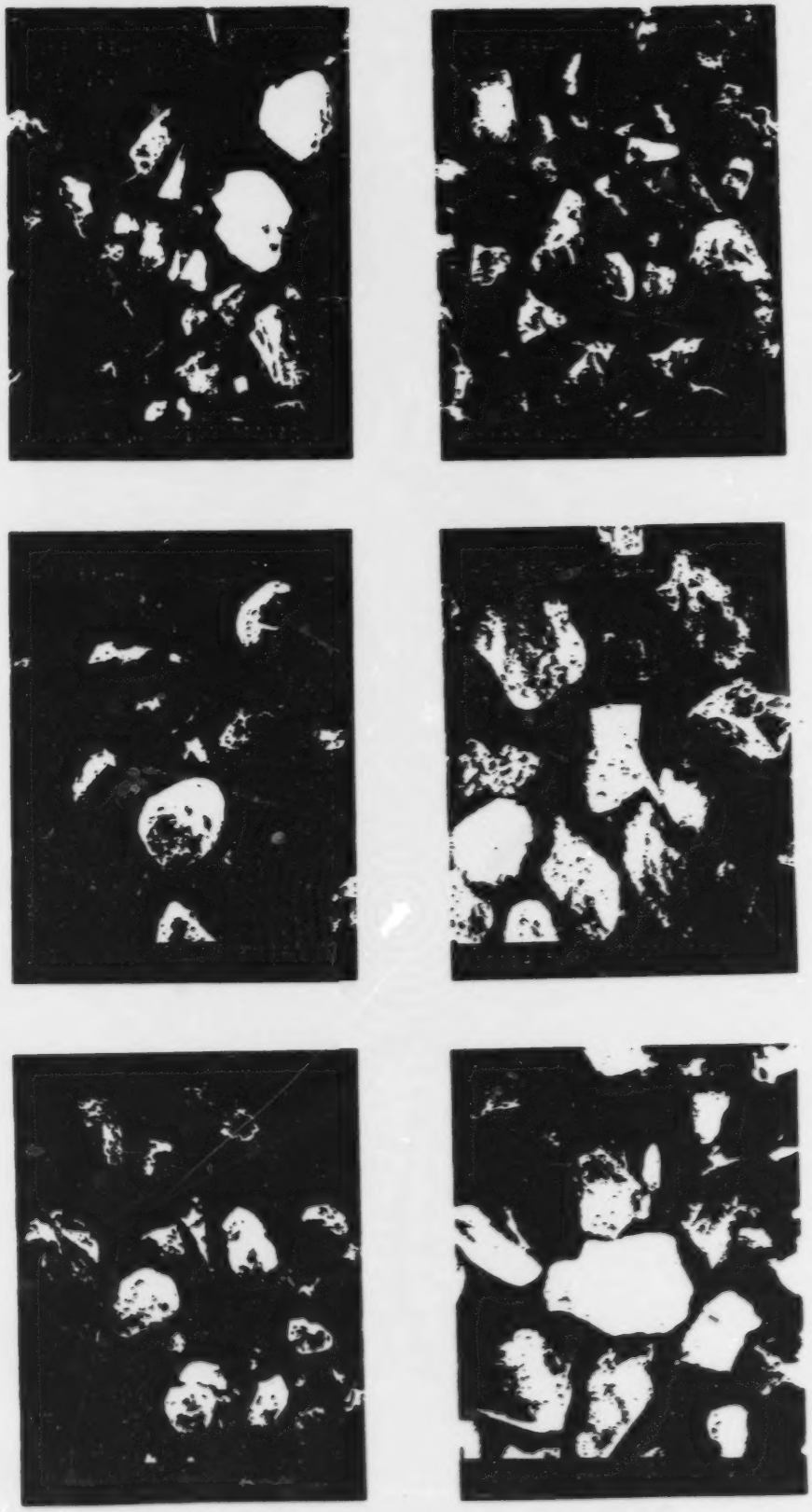

Figure 4. SEM of Different Sands and Fines

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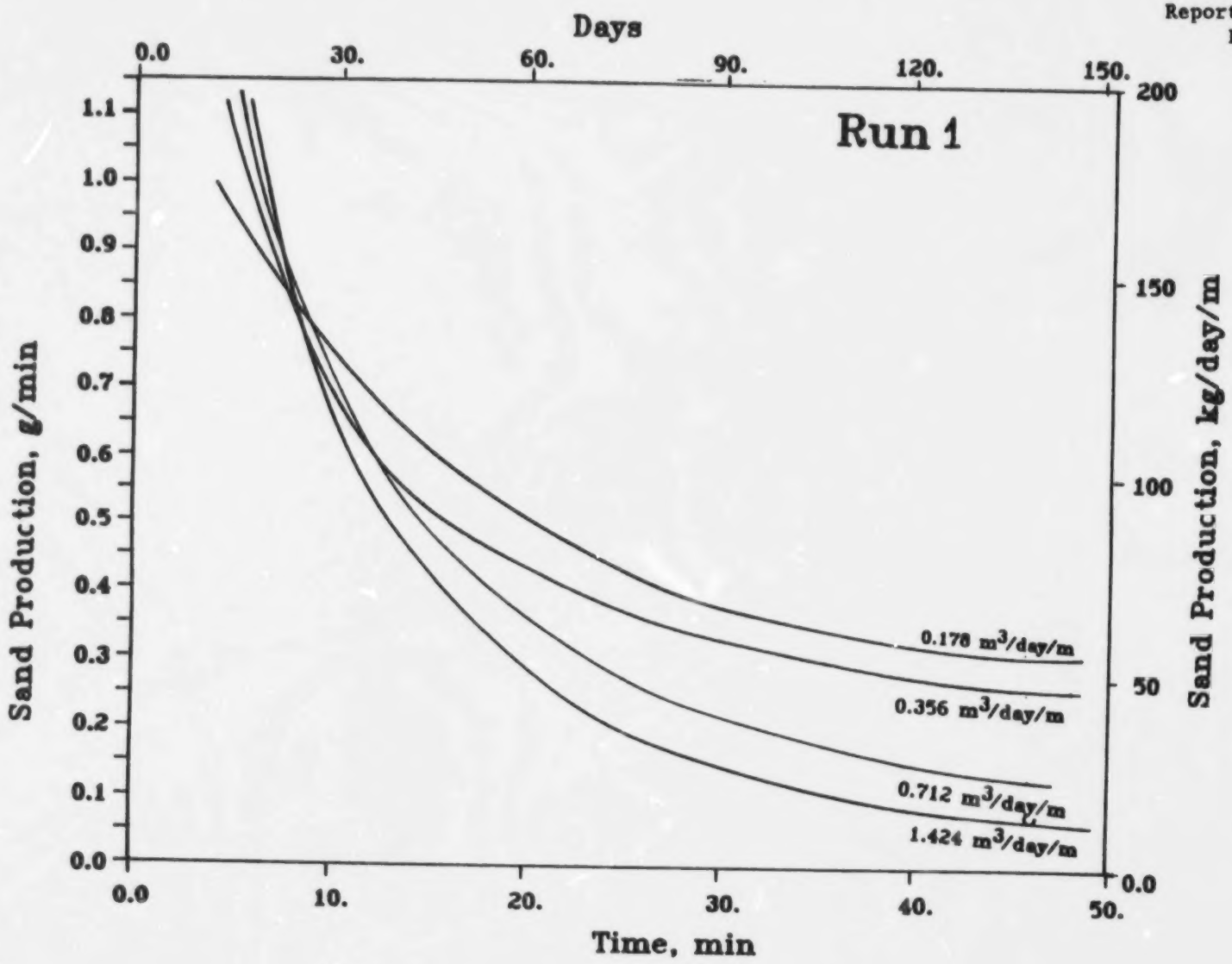

Figure 5. Sand Production Behavior as a Function of Flow Rates for Run 1

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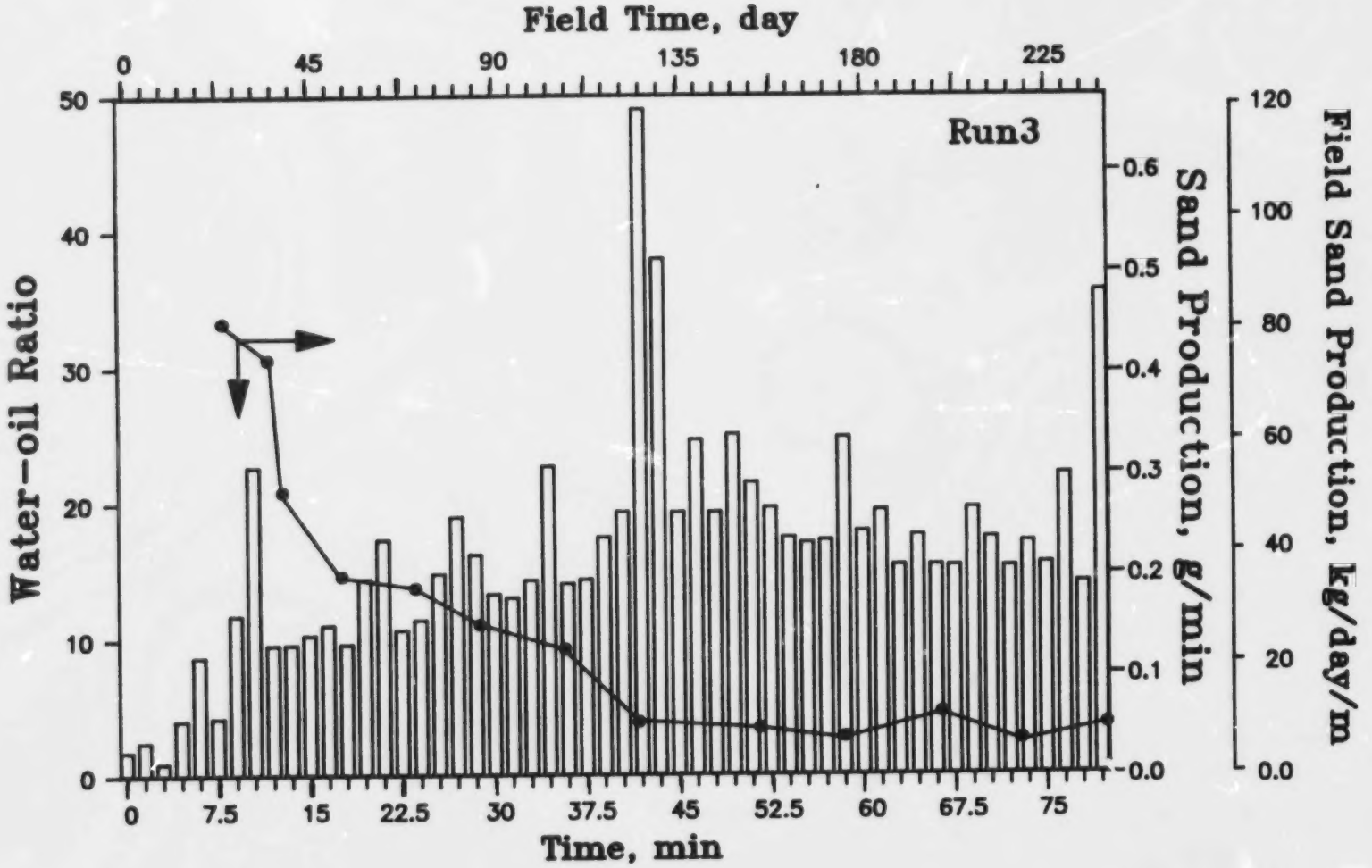

Figure 6. Sand Production and WOR for Run 3.

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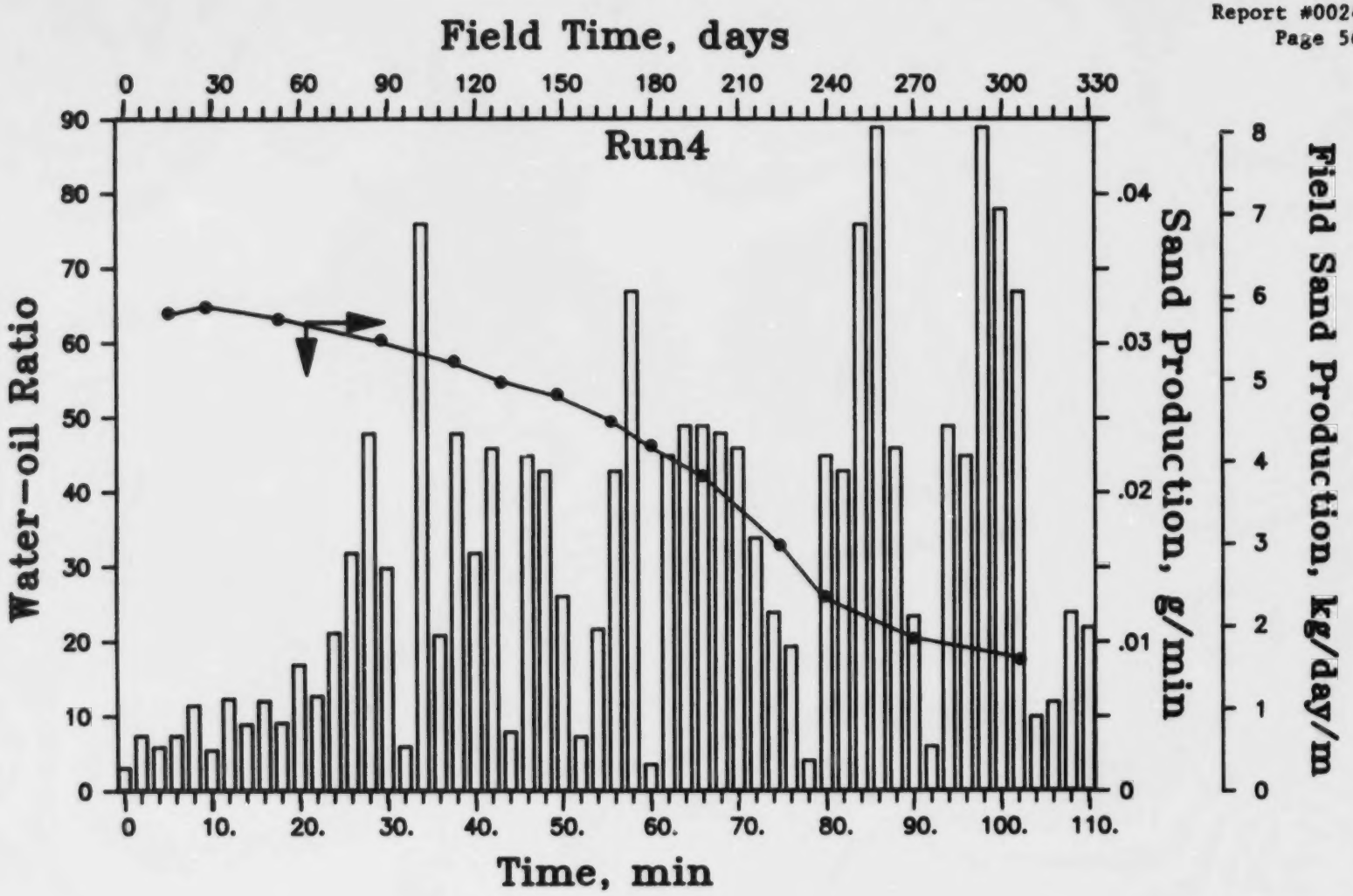

Figure 7. Sand Production and WOR for Run 4.

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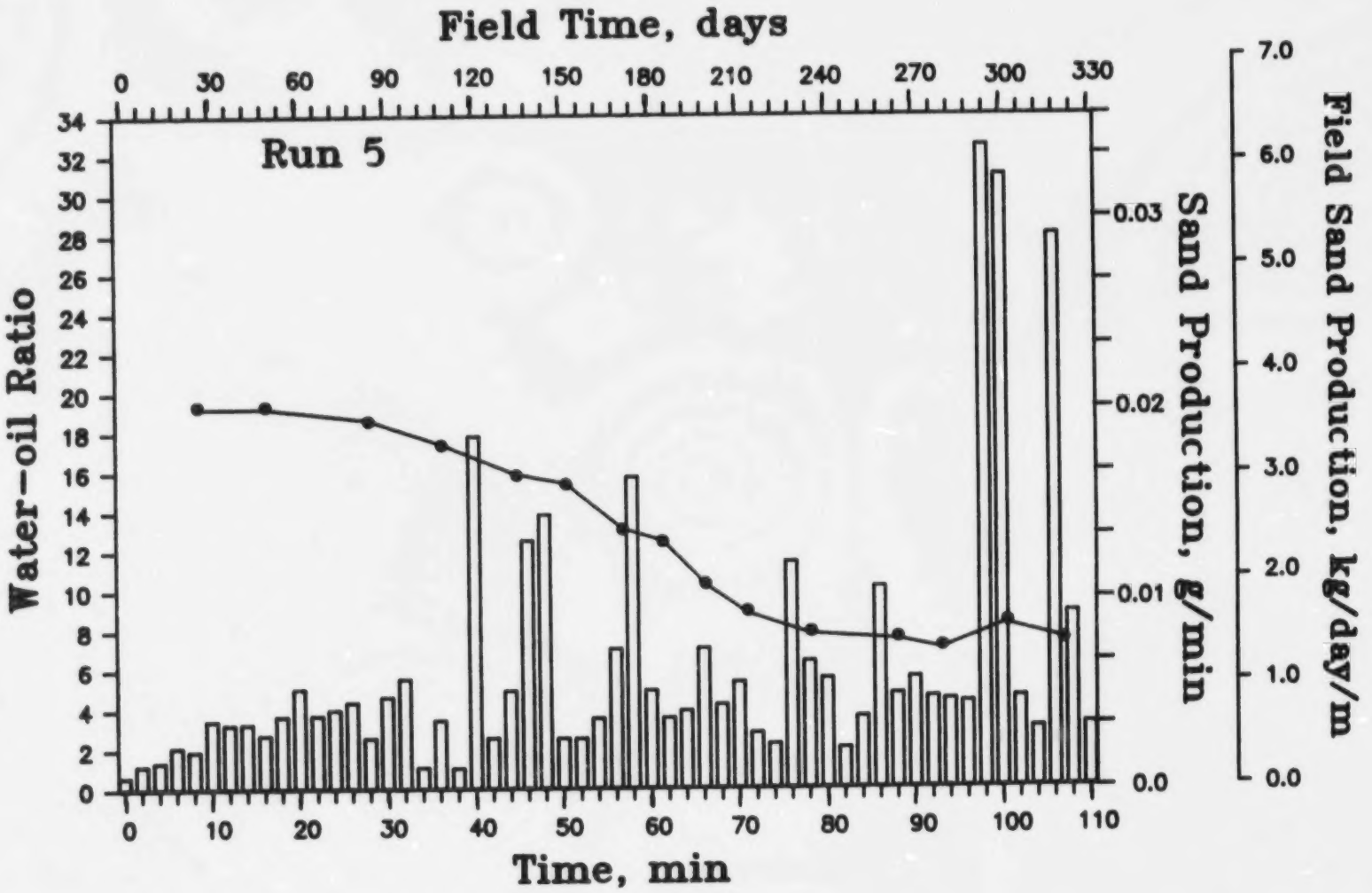

Figure 8. Sand Production and WOR for Run 5.

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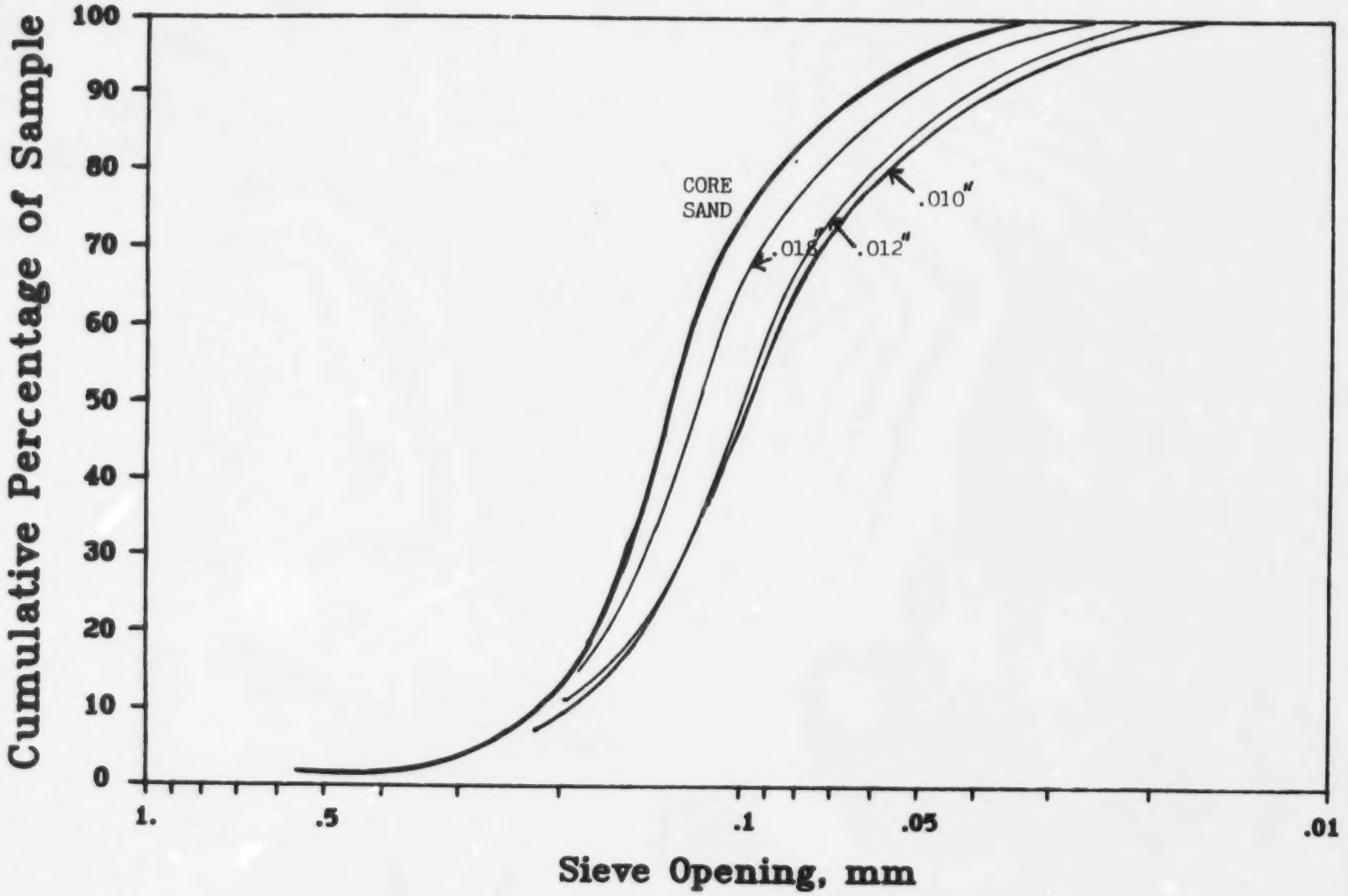

Figure 9. Particle Size Distribution of Trapped Sands (Runs 3,4 and 5)

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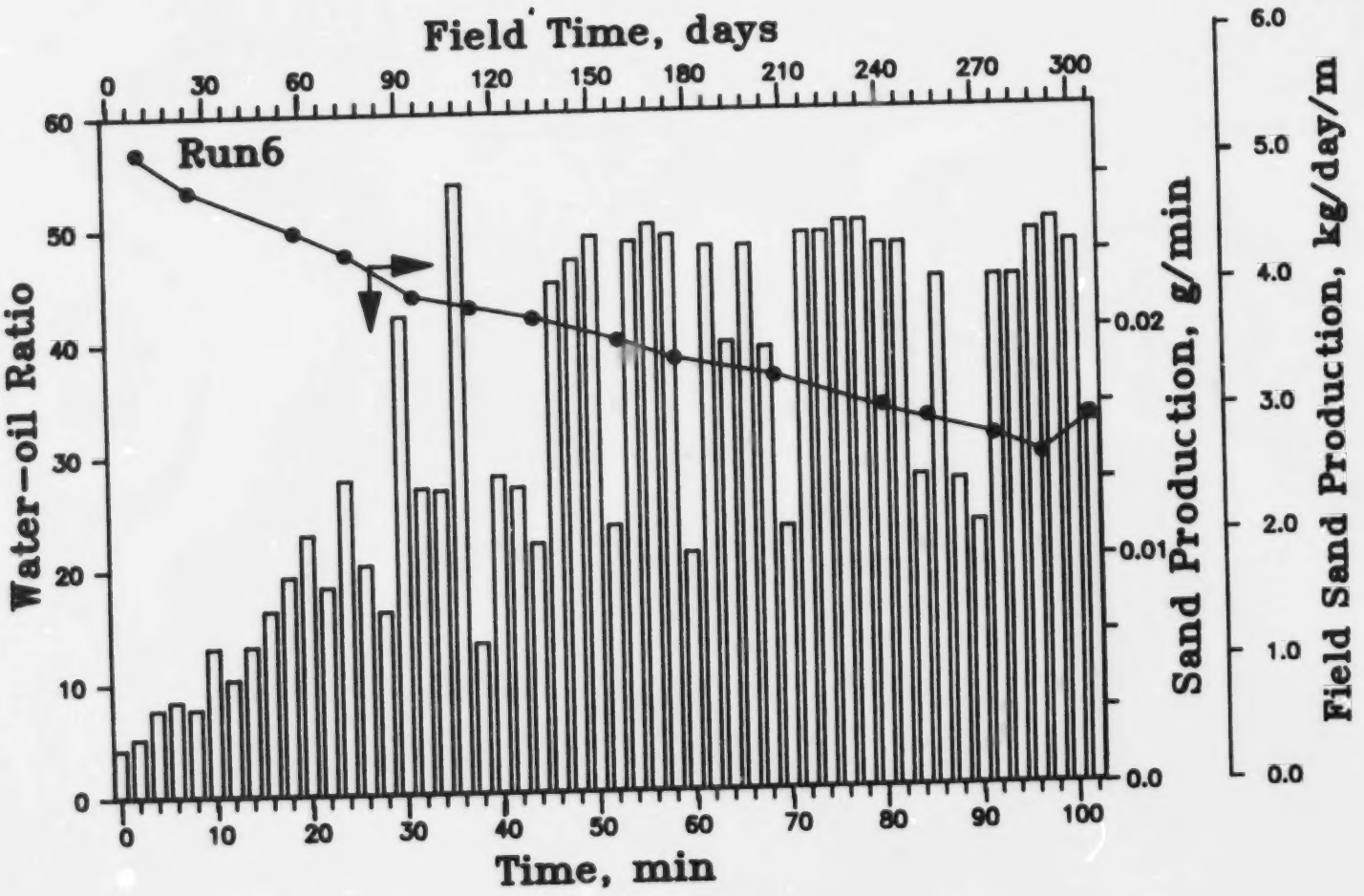

Figure 10. Sand Production and WOR for Run 6.

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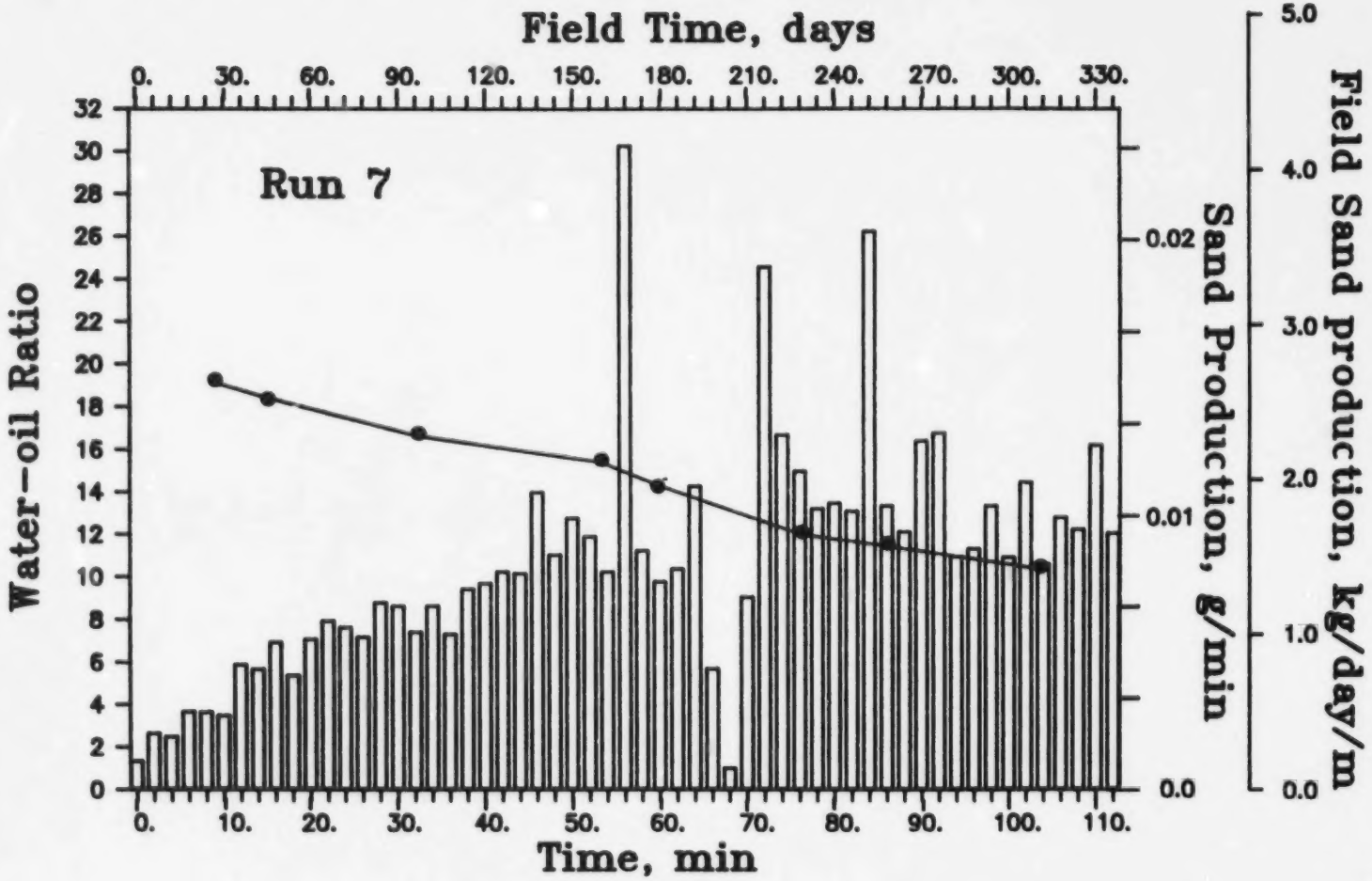

Figure 11. Sand Production and WOR for Run 7.

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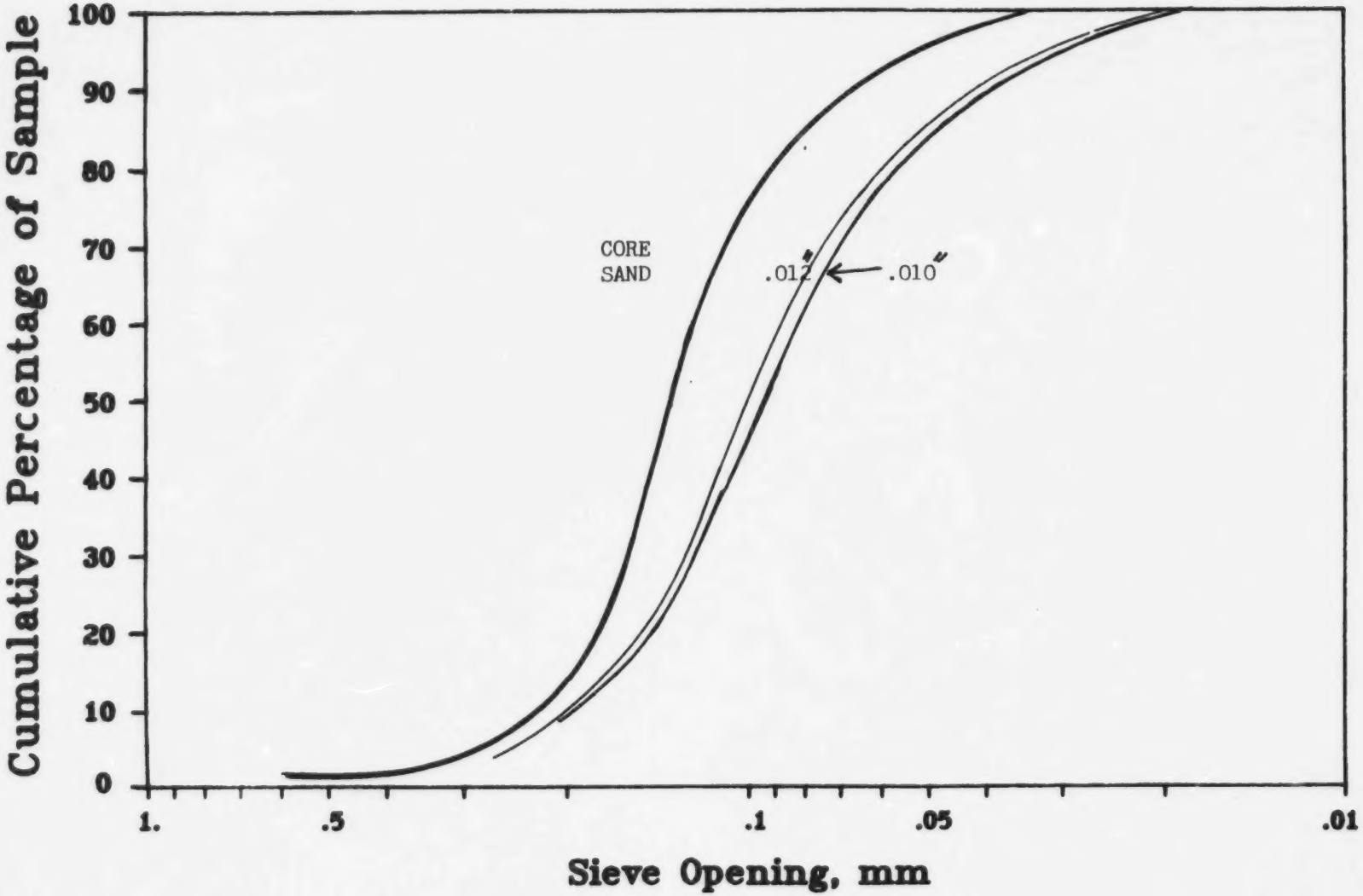

Figure 12. Particle Size Distribution of Trapped Sands (Runs 6 and 7)

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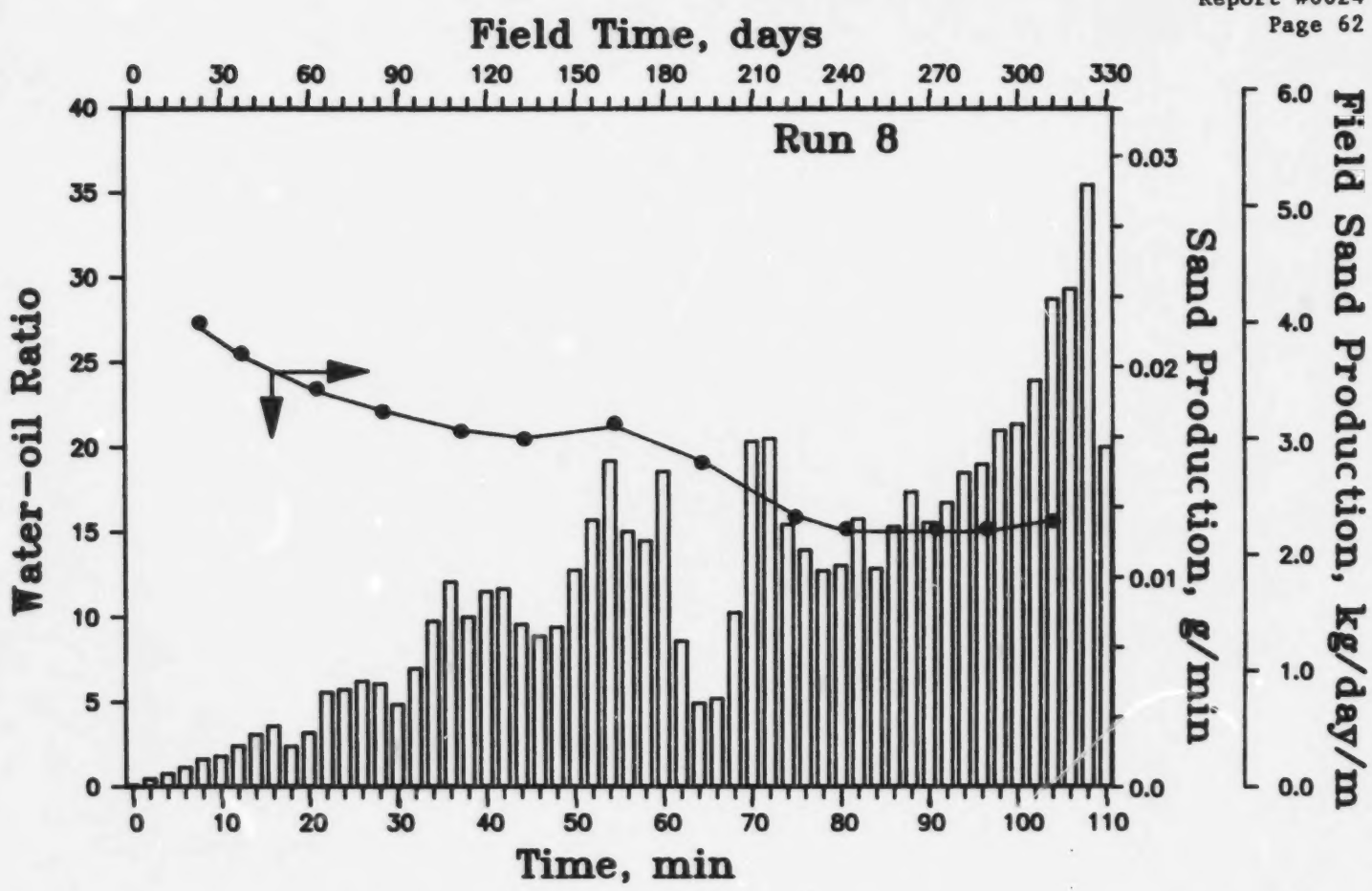

Figure 13. Sand Production and WOR for Run 8.

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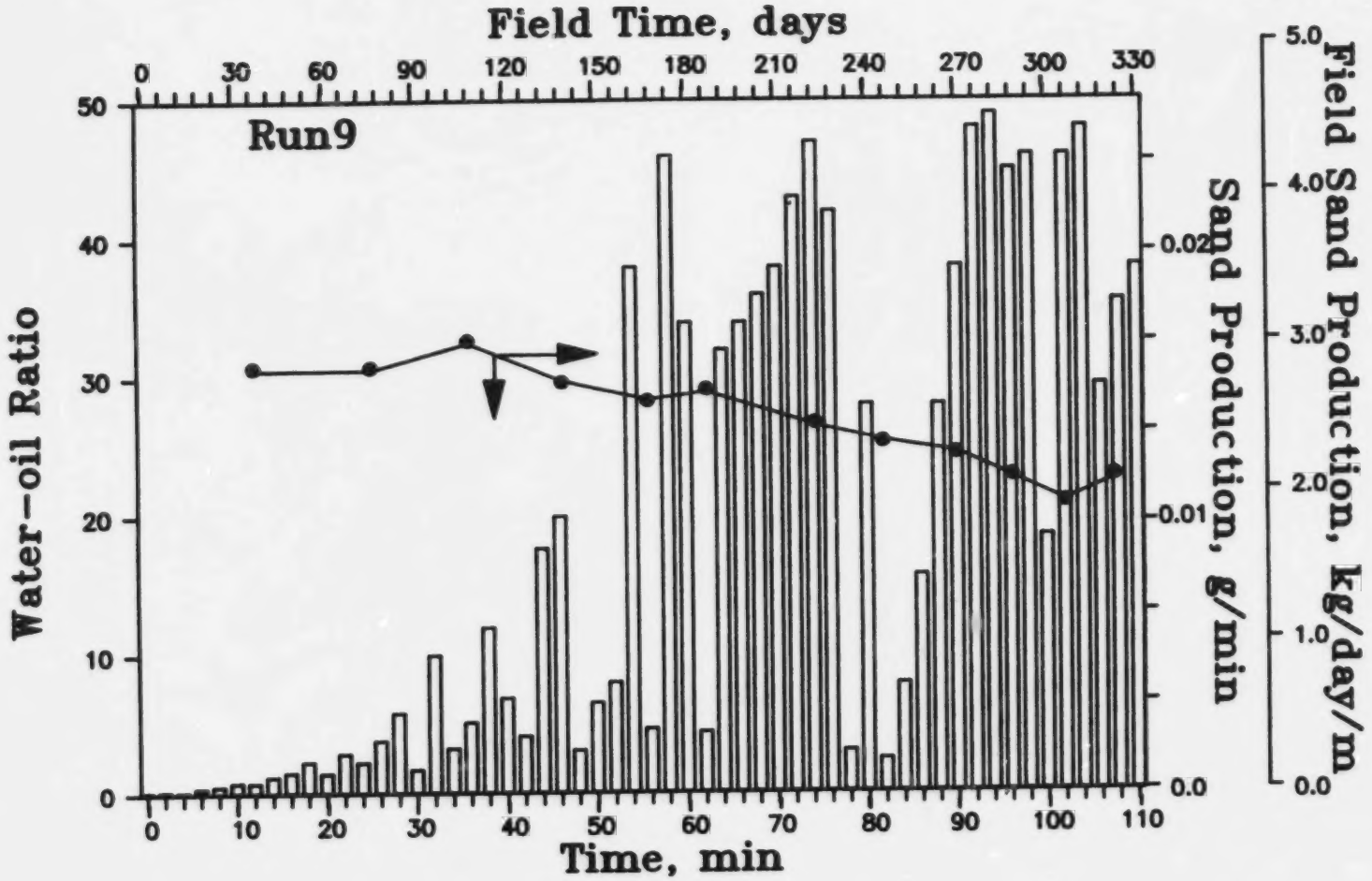

Figure 14. Sand Production and WOR for Run 9.

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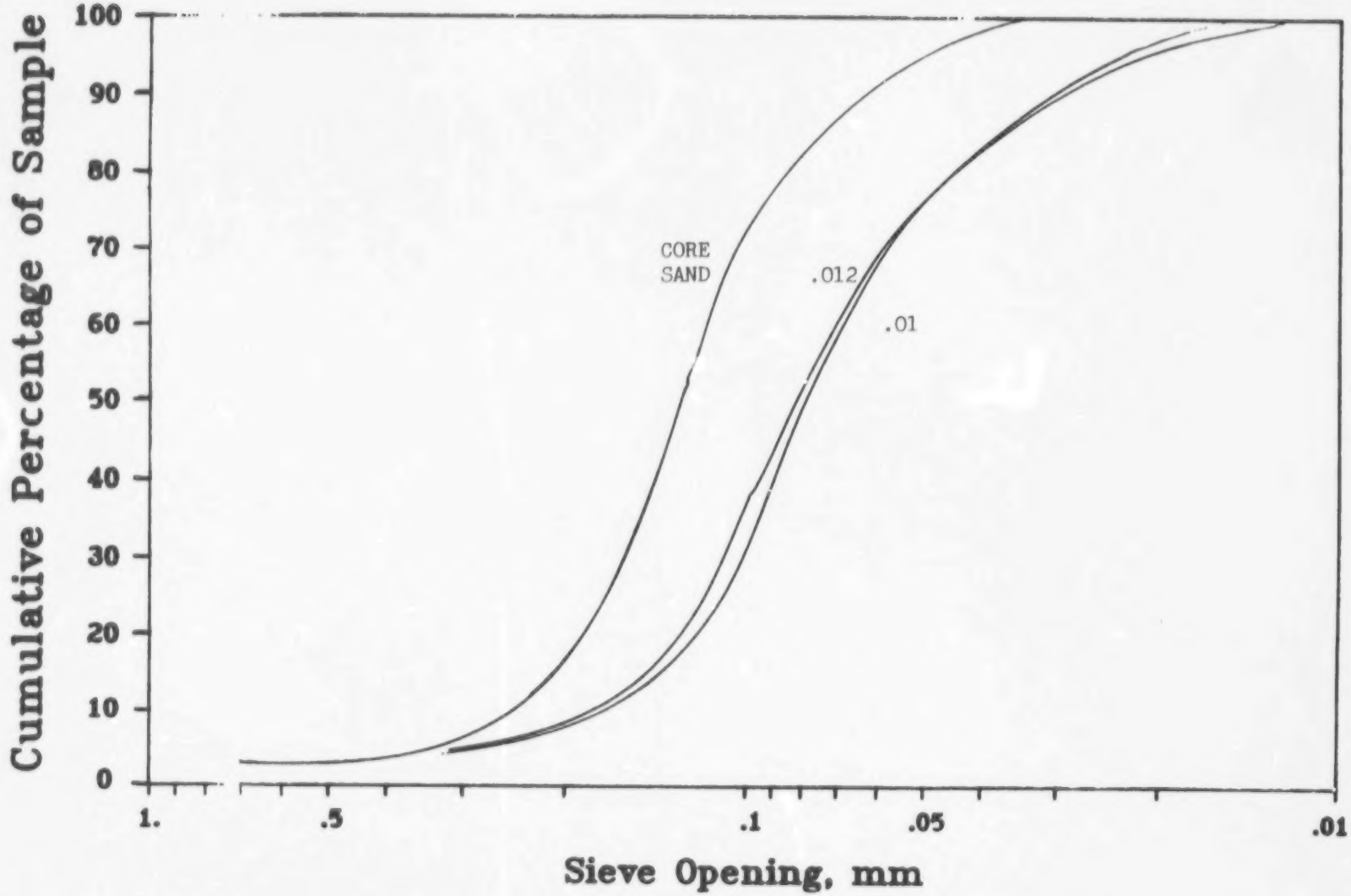

Figure 15. Particle Size Distribution of Trapped Sands (Runs 8 and 9)

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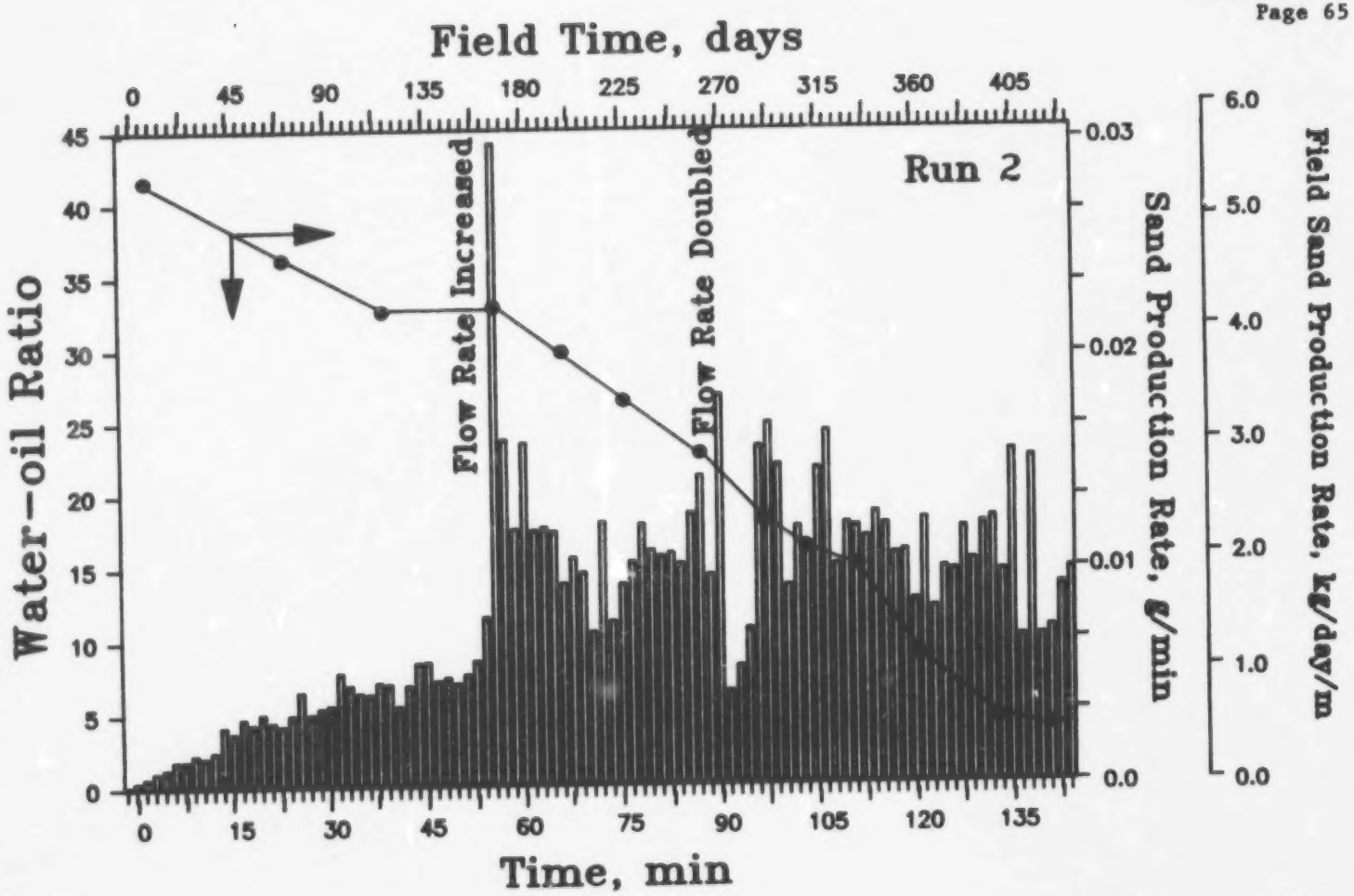

Figure 16. Sand Production and WOR for Run 2.

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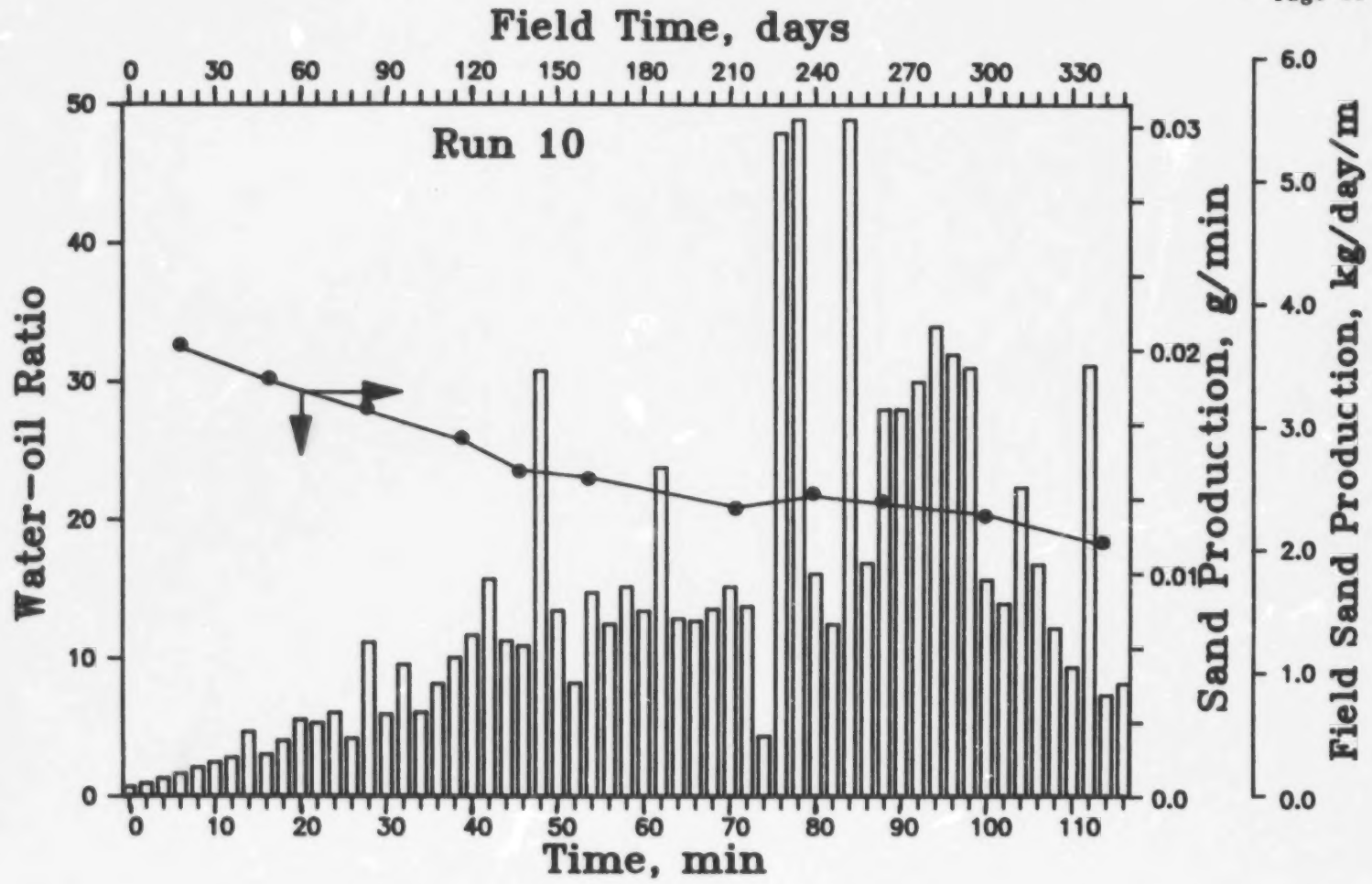

Figure 17. Sand Production and WOR for Run 10.

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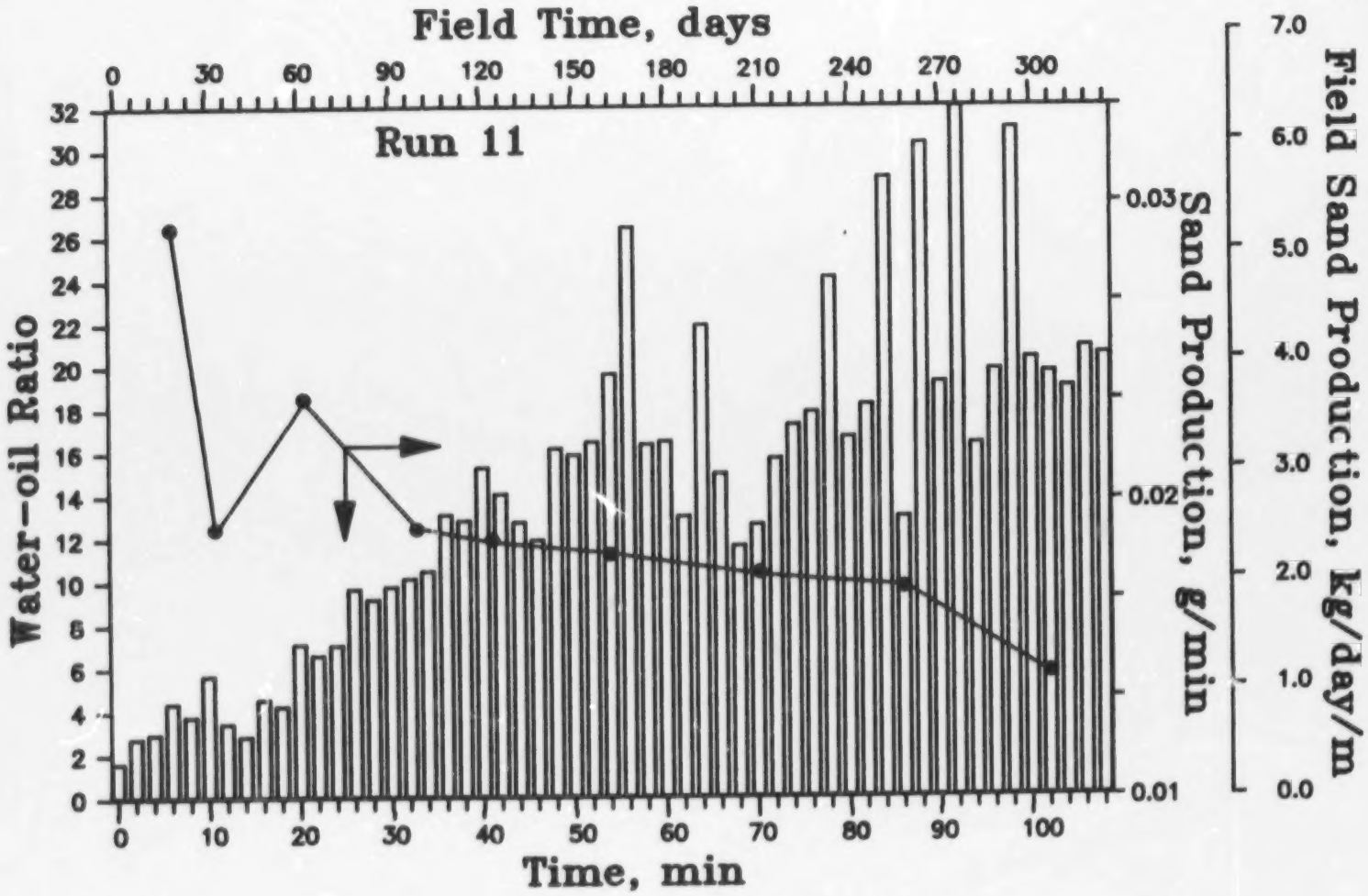

Figure 18. Sand Production and WOR for Run 11.

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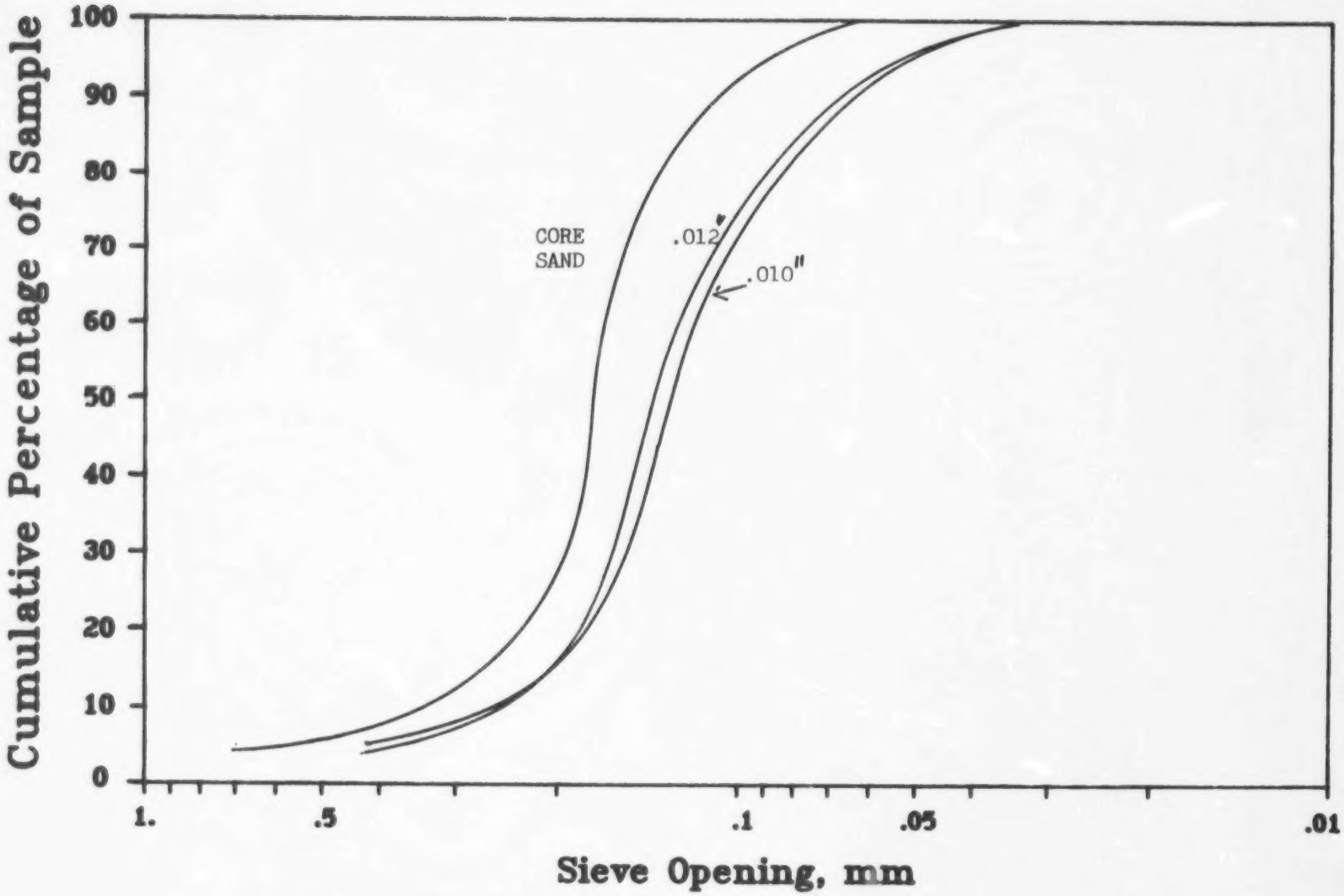

Figure 19. Particle Size Distribution of Trapped Sands (Runs 10 and 11)

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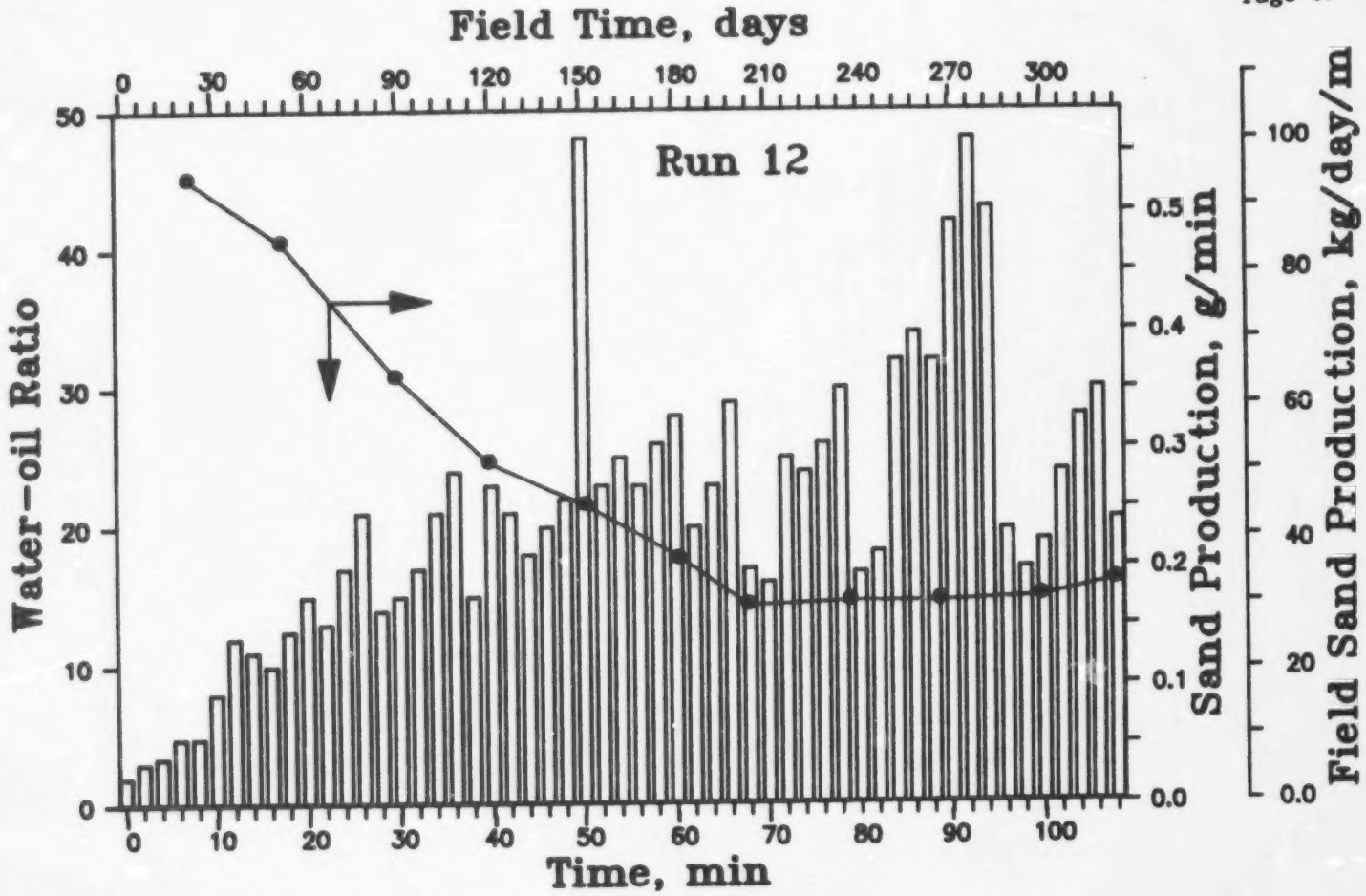

Figure 20. Sand Production and WOR for Run 12.

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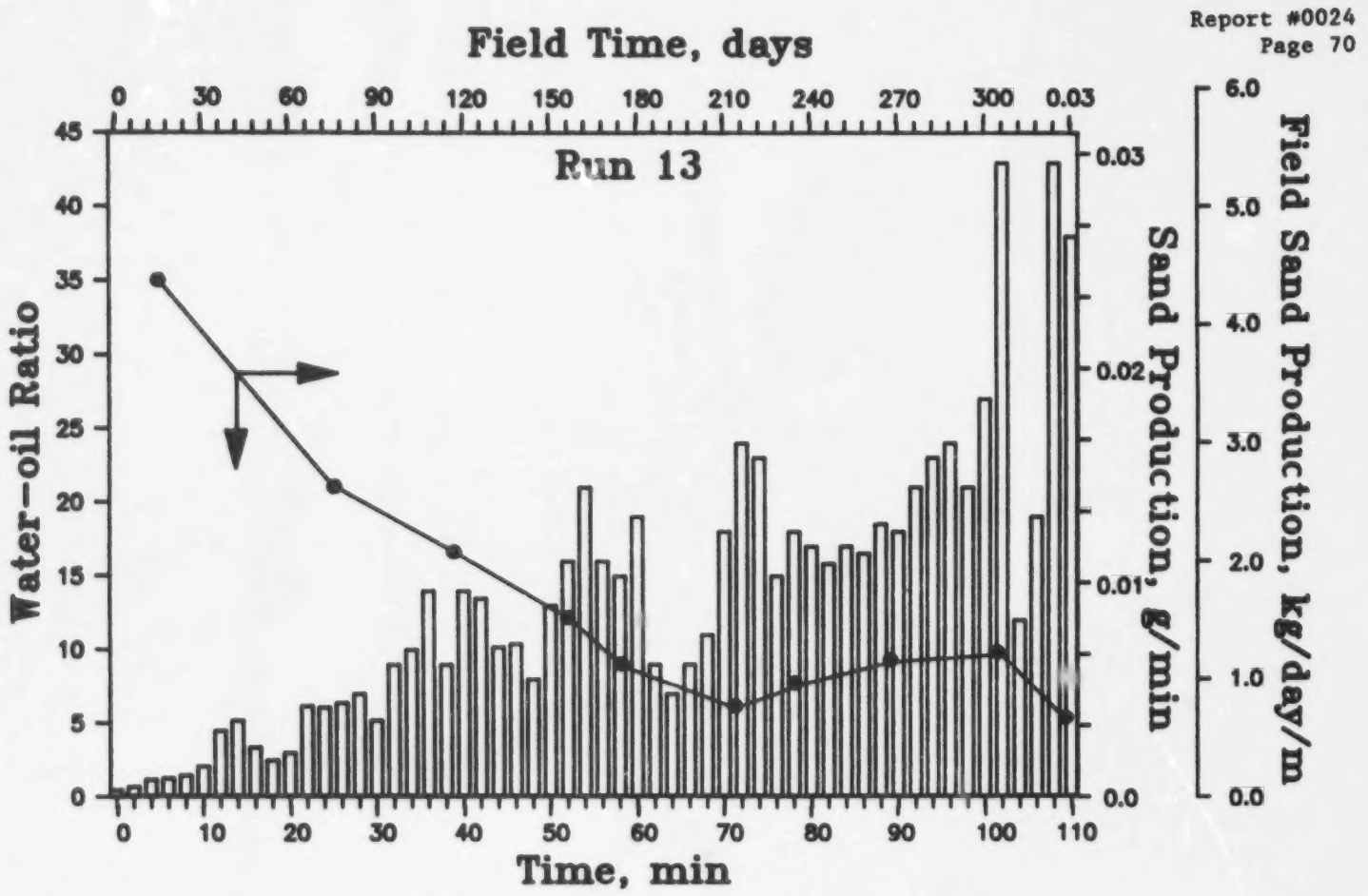

Figure 21. Sand Production and WOR for Run 13.

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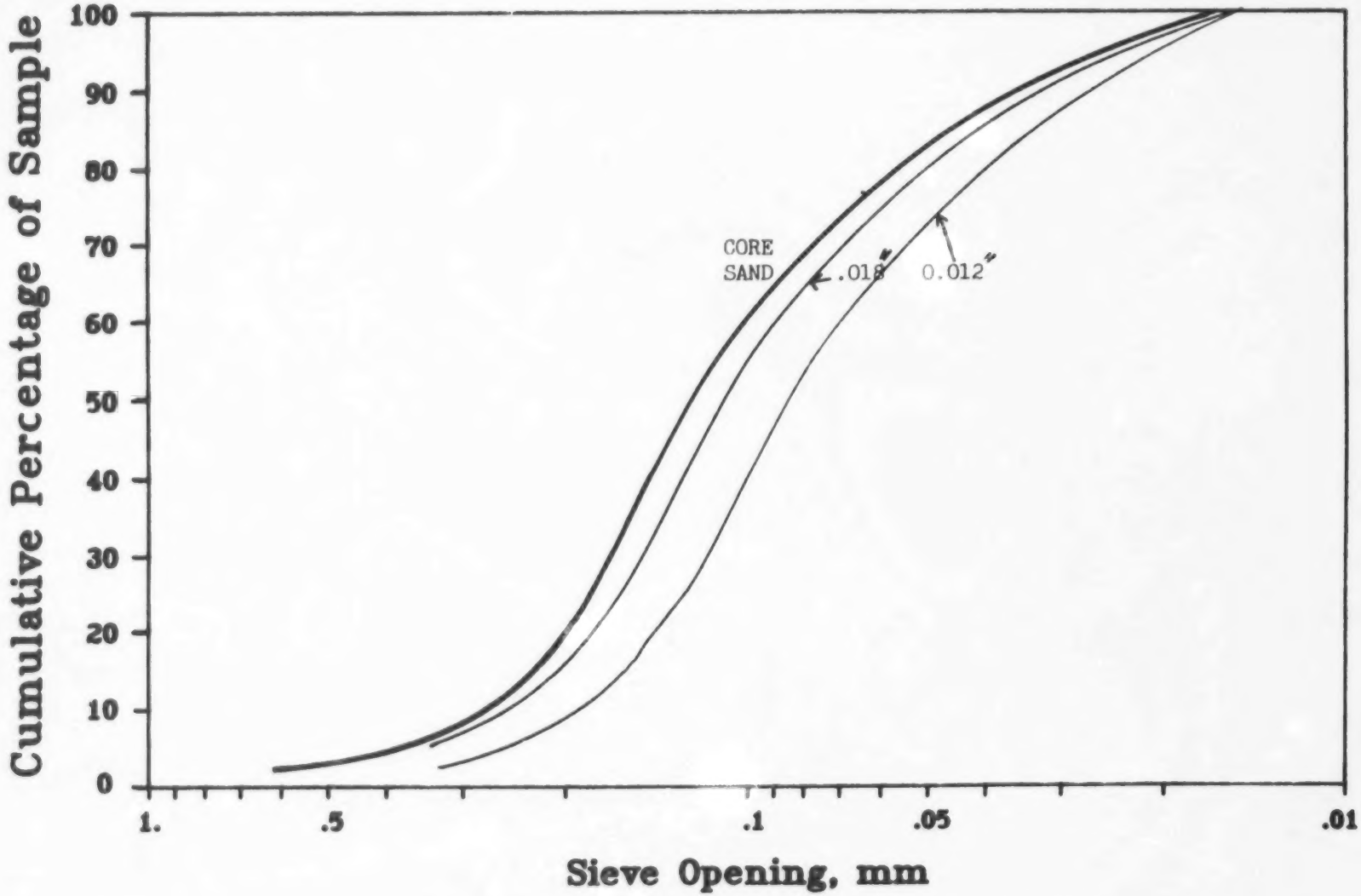

Figure 22. Particle Size Distribution of Trapped Sands (Runs 12 and 13)

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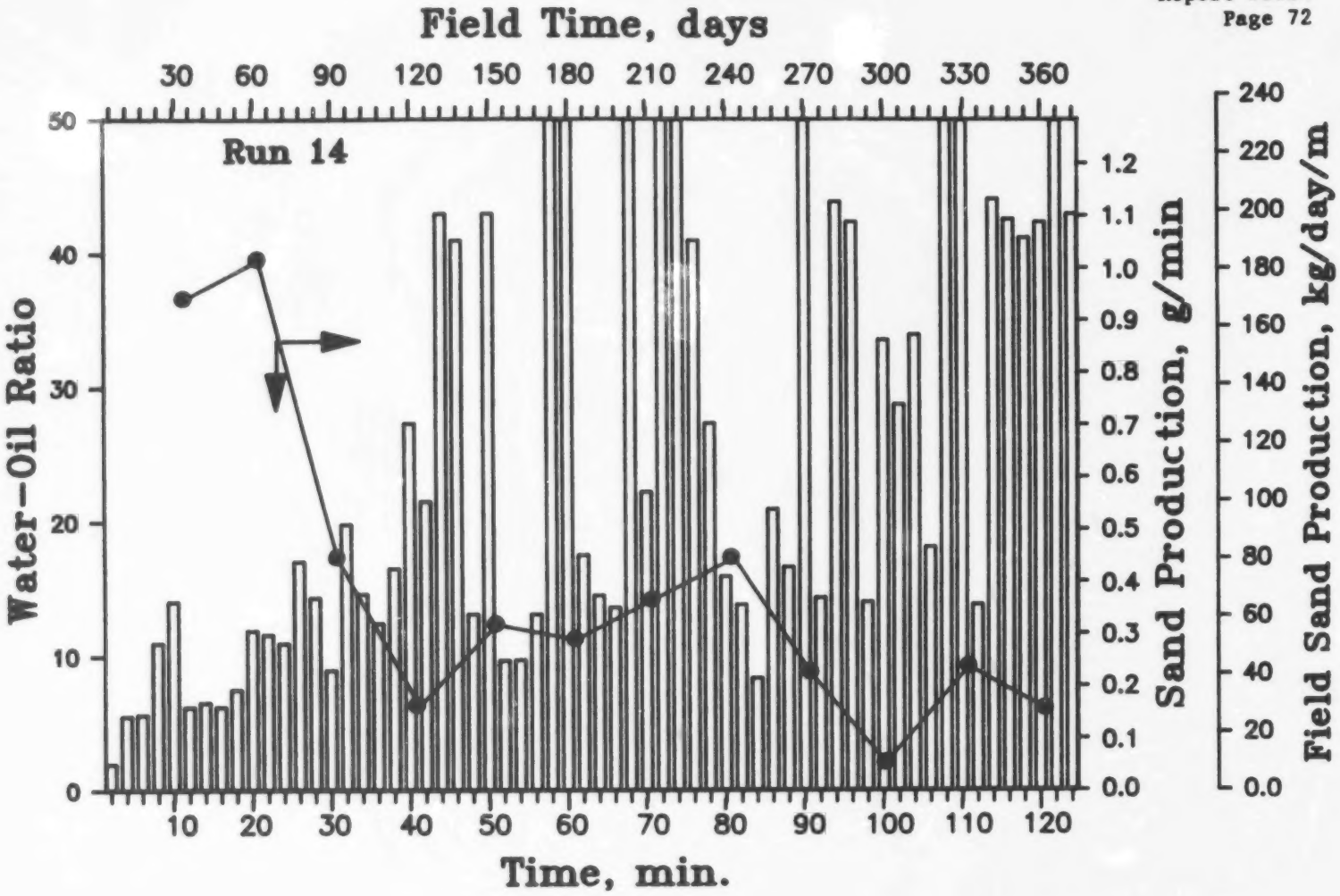

Figure 23. Sand Production and WOR for Run 14.

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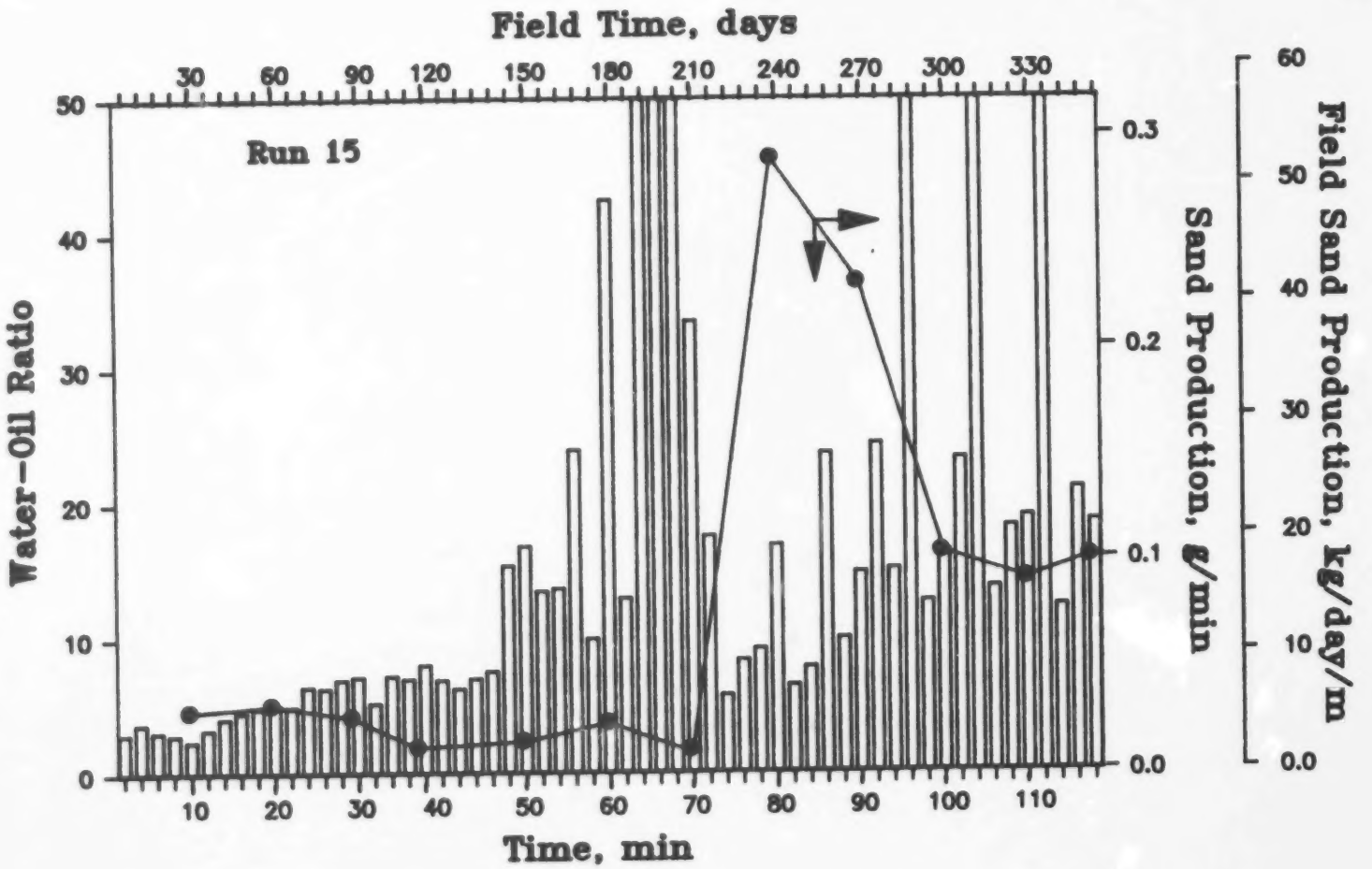

Figure 24. Sand Production and WOR for Run 15.

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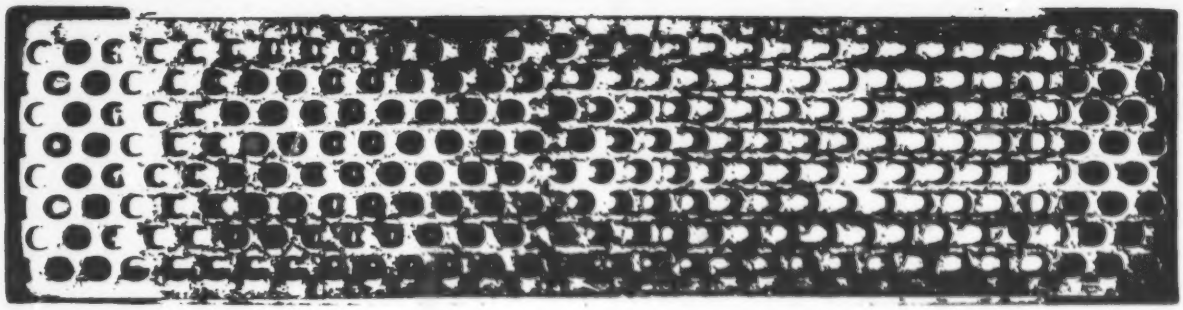

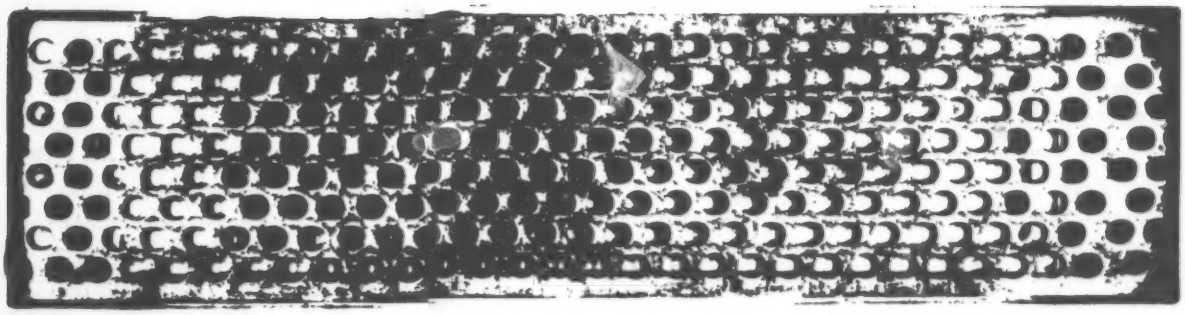

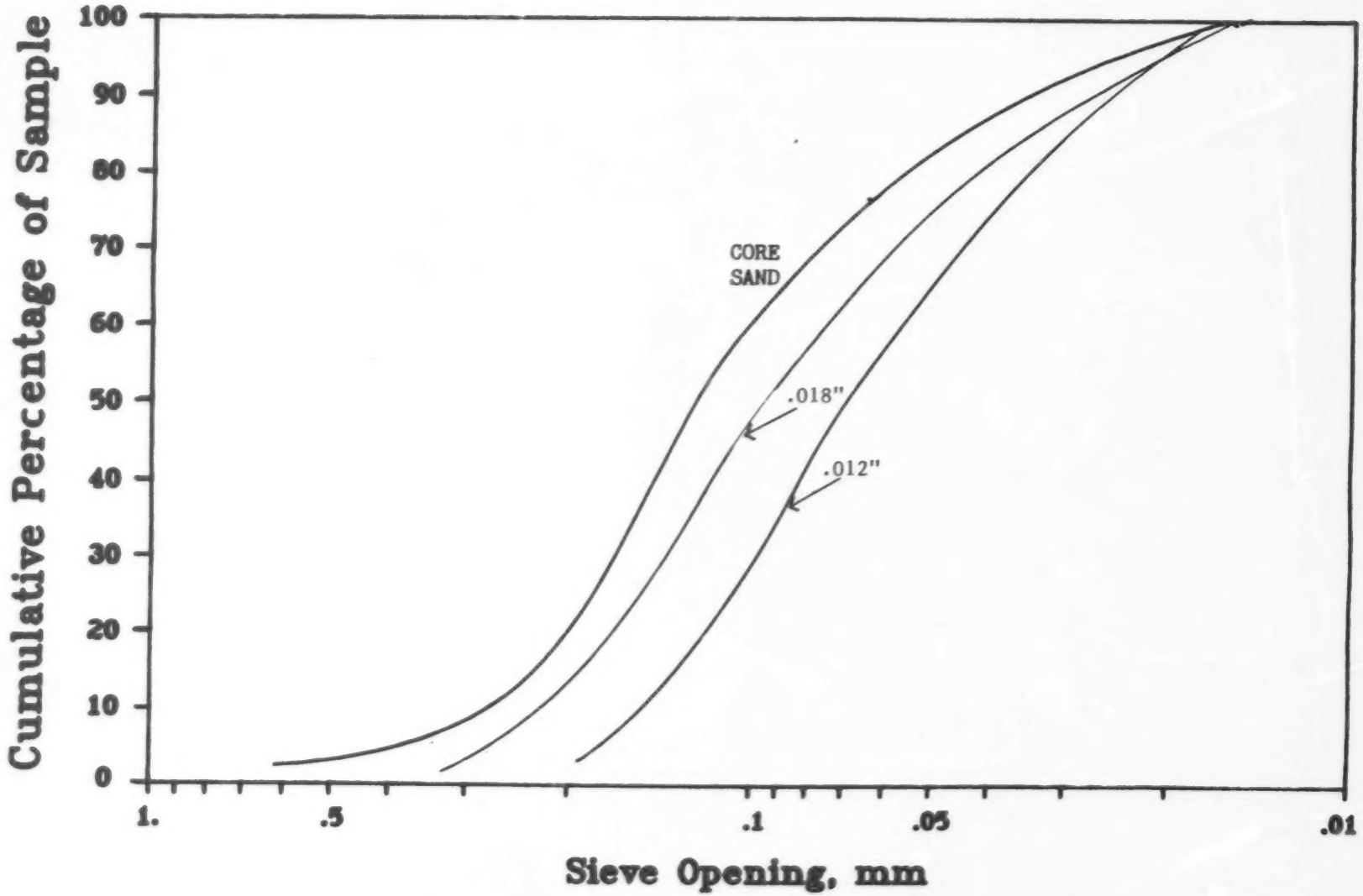

Figure 25. Particle Size Distribution of Trapped Sands (Runs 14 and 15)

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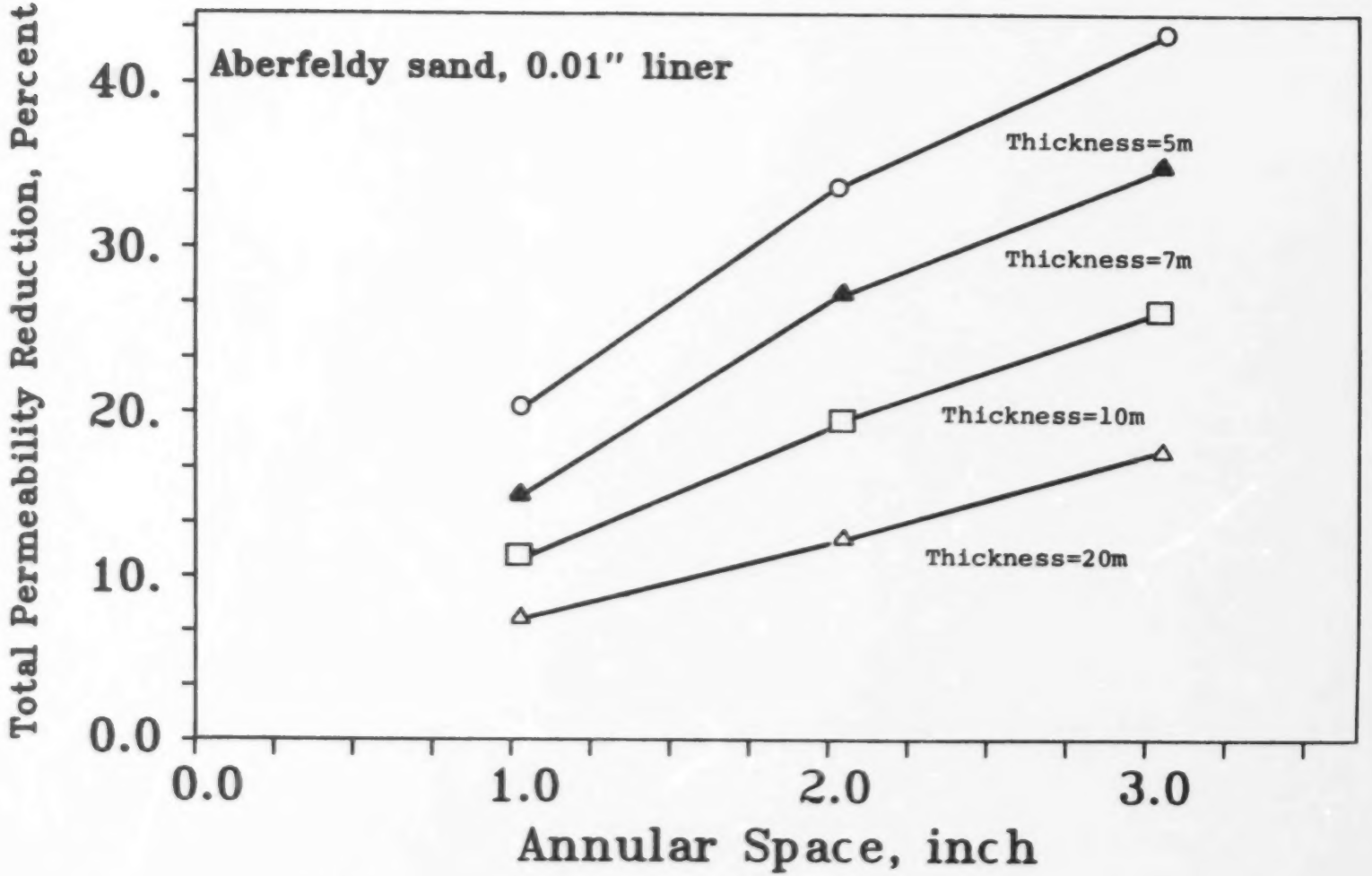

Figure 26. Permeability Reduction for Various Ann. Space and Thickness

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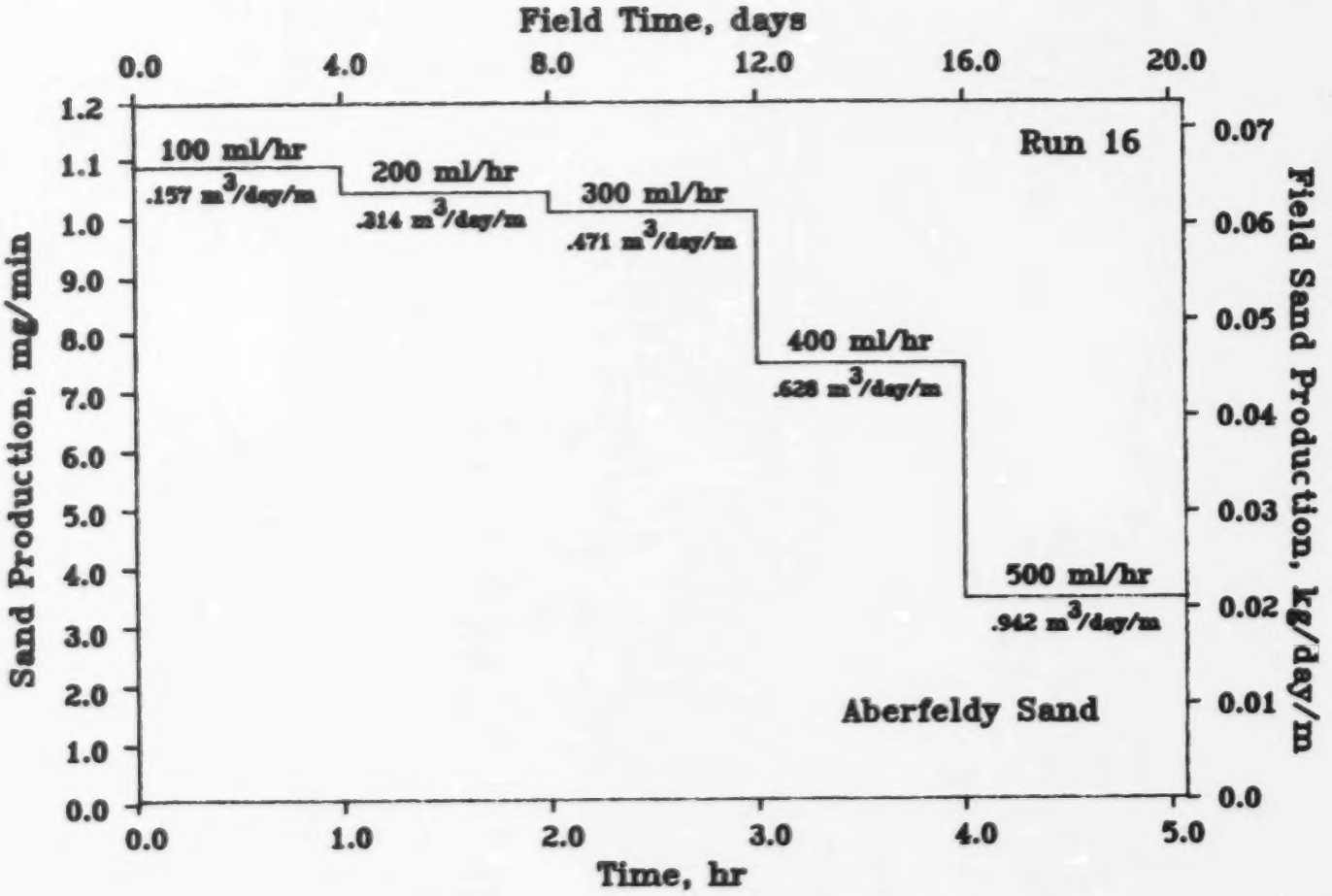

Figure 27. Sand Production for Run 16 (Aberfeldy sand)

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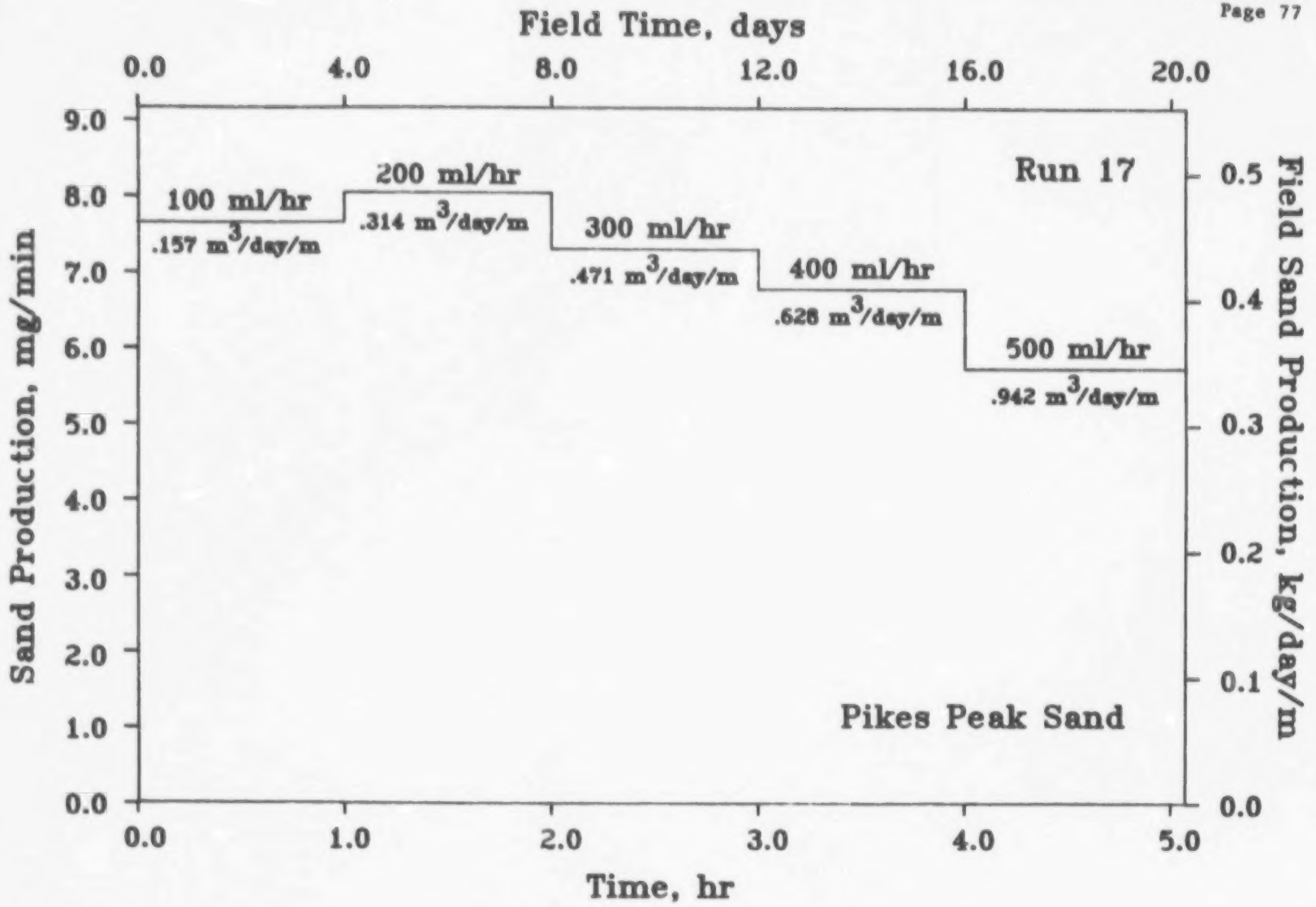

Figure 28. Sand Production for Run 17

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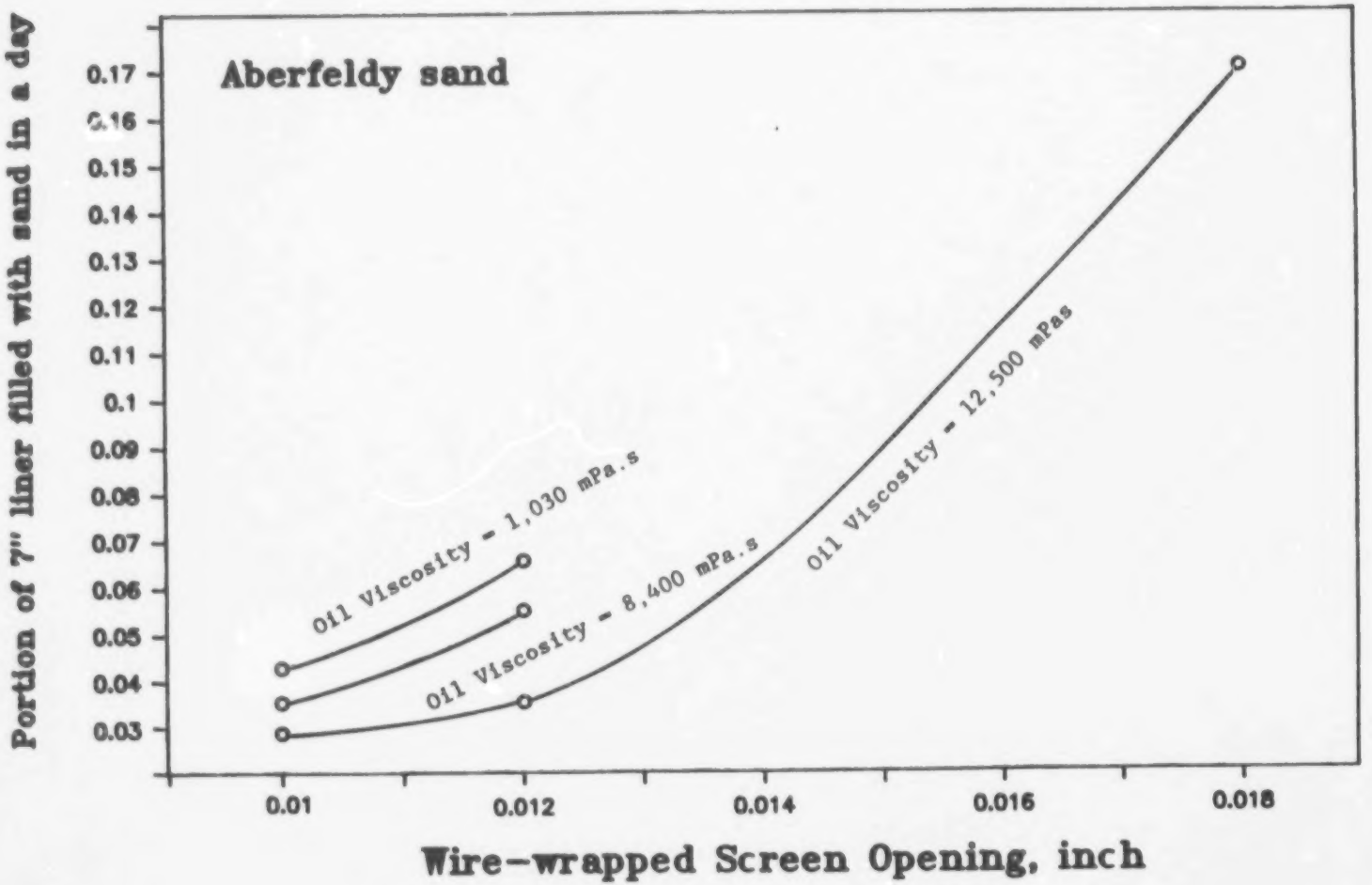

Figure 29. Sand Deposit for Aberfeldy sands

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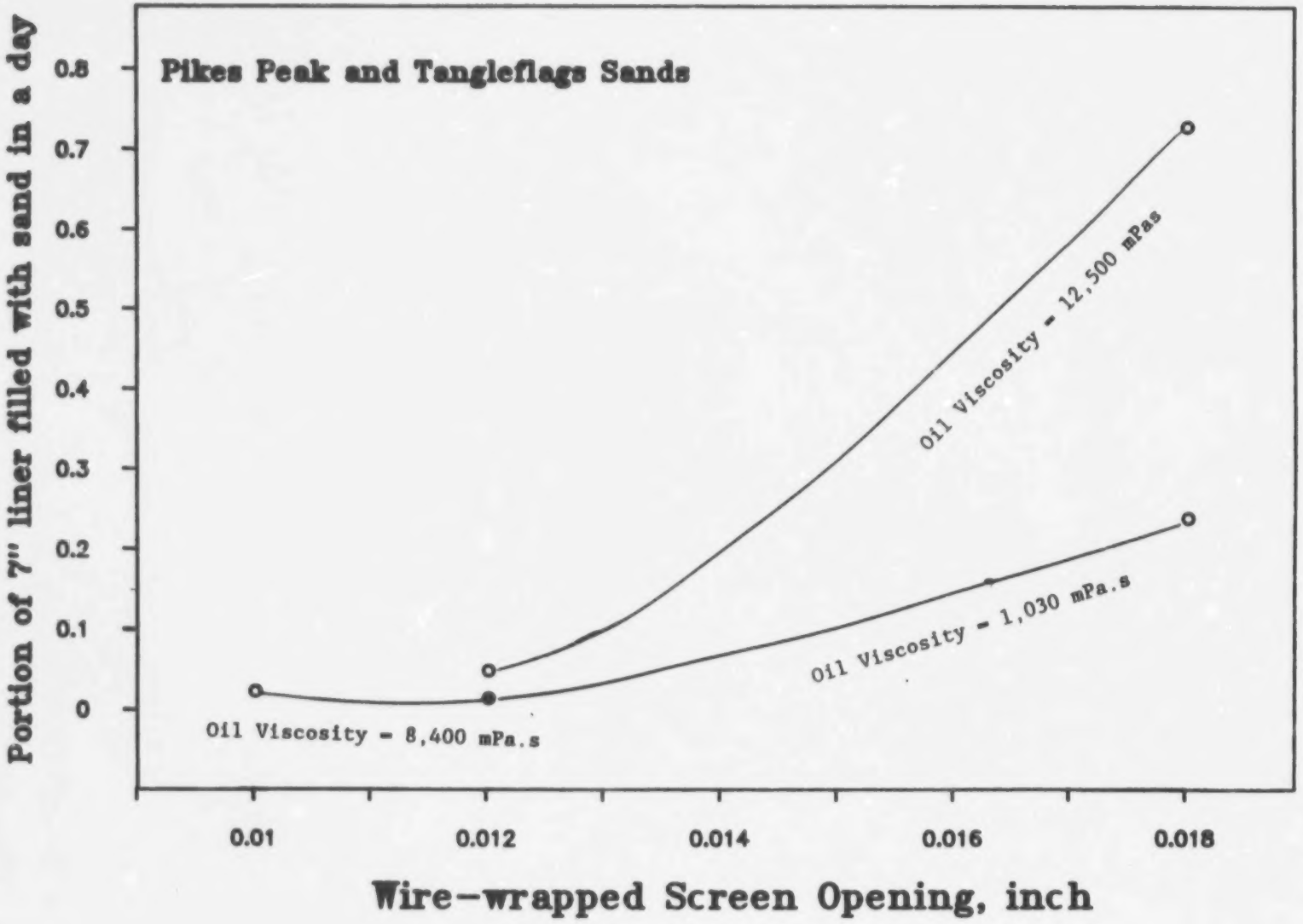

Figure 30. Sand Deposits for Pikes Peak and Tangleflags Sands

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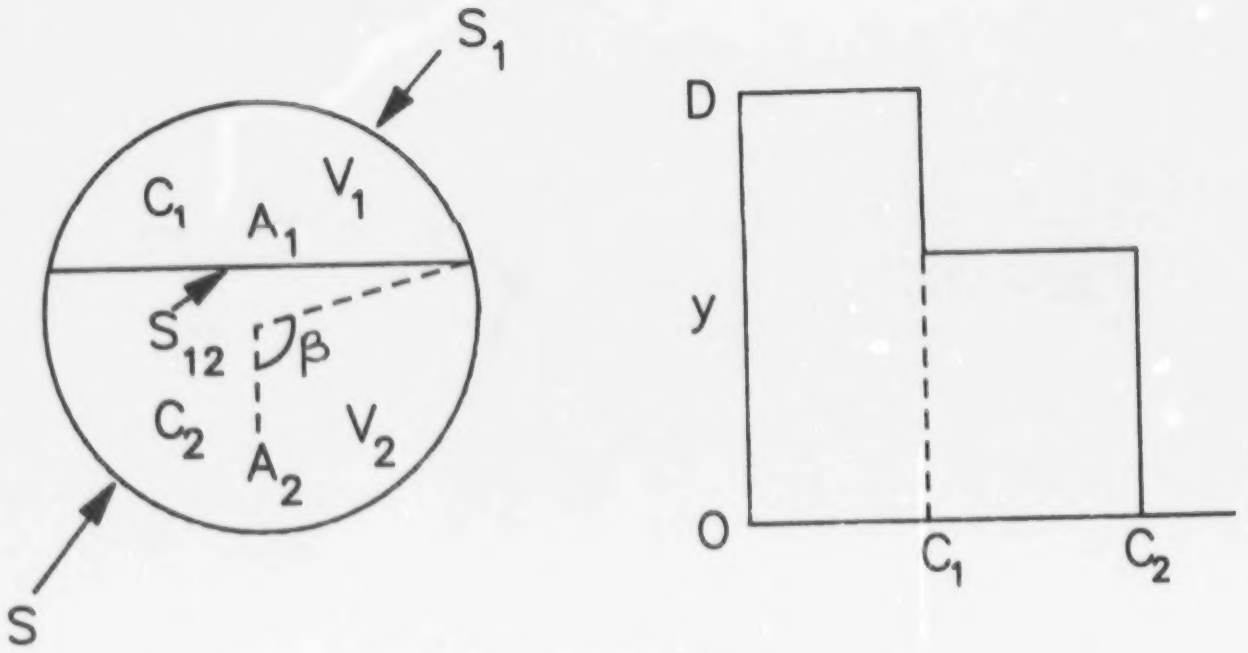

Figure 31. Two-layer Model Depiction

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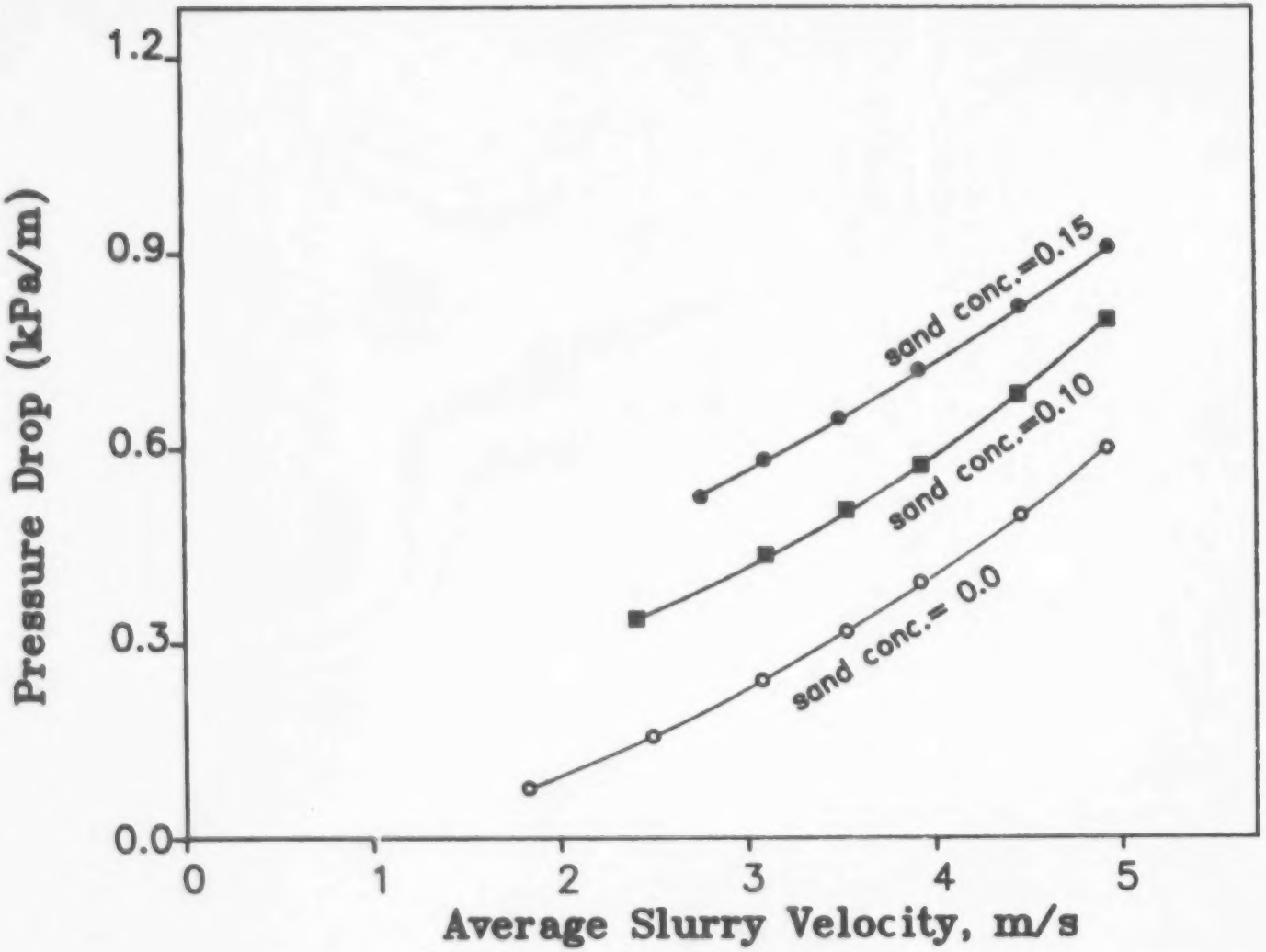

Figure 32. Pressure Drop for Sand Carrying Fluid

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